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THESIS

NAVAL POSTGRADUATE SCHOOL SOLAR CELL ARRAY TESTER

by

Kevin J. Smith

December 2010

Thesis Advisor:	James H. Newman
Second Reader:	Daniel J. Sakoda

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Educating space professionals is an expensive endeavor. The use of technologies such as CubeSats can cut the cost giving space professionals real world experience in satellite design, testing, integration and operations. The Naval Postgraduate School-Solar Cell Array Tester (NPS-SCAT) will be the first of what may be many CubeSats developed by the Space Systems Academic Group, Small Satellite Laboratory. This thesis analyzes the NPS-SCAT program from the program manager's point of view and provides an overview of the development of the program from an un-qualified Engineering Design Unit (EDU) to a fully qualified EDU. Also included in this thesis is a description of the subsystems and full cost analysis that covers the total costs from concept to flight unit.

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NAVAL POSTGRADUATE SCHOOL SOLAR CELL ARRAY TESTER

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
December 2010

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ABSTRACT

Educating space professionals is an expensive endeavor. The use of technologies such as CubeSats can cut the cost giving space professionals real world experience in satellite design, testing, integration and operations. The Naval Postgraduate School-Solar Cell Array Tester (NPS-SCAT) will be the first of what may be many CubeSats developed by the Space Systems Academic Group, Small Satellite Laboratory. This thesis analyzes the NPS-SCAT program from the program manager's point of view and provides an overview of the development of the program from an un-qualified Engineering Design Unit (EDU) to a fully qualified EDU. Also included in this thesis is a description of the subsystems and full cost analysis that covers the total costs from concept to flight unit.

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LIST OF ACRONYMS AND ABBREVIATIONS

1U	One Unit CubeSat
2U	Two Unit CubeSat
AA	Autonomous Actions
ACS	Attitude Control Subsystem
ADCS	Attitude Determination and Control Subsystem
ASFCR	Amateur Satellite Frequency Coordination Request
AM	Air Mass
ARC	Ames Research Center
BTJM	Triple Junction with Monolithic Diode Solar Cell
C&DH	Command and Data Handler
CA	Command Actions
CAD	Computer Aided Design
Cal Poly	California Polytechnic State University
CDS	CubeSat Design Specification
cm	Centimeters
COTS	Commercial-Off-The-Shelf
CONOPS	Concept of Operations
CPT	Comprehensive Performance Test
CSK	CubeSat Kit
DoD	Department of Defense
EDU	Engineering Design Unit
EELV	Evolved Expendable Launch Vehicle
EPS	Electrical Power Subsystem
EPS1	First Revision of Clyde Space EPS
EPS2	Second Revision of Clyde Space EPS
ESP	Experimental Solar Panel
ESPA	EELV Secondary Payload Adapter
FHSS	Frequency Hopping Spread Spectrum
FY	Fiscal Year

GEVS	General Environment Verification Specification
GHz	Gigahertz
I^2C	Inter-Integrated Circuit
IC	Integrated Circuit
ISM	Industrial, Scientific, and Medical
ISS	International Space Station
ITJ	Improved Triple Junction
kB	kilobyte
kg	kilogram
km	kilometer
KPP	Key Performance Parameters
Lbs	Pounds
LEO	Low Earth Orbit
LV	Launch Vehicle
mm/s	millimeters/second
MEPSI	Micro Electrical-Mechanical Propulsion Systems
MHz	Megahertz
MIT	Massachusetts Institute of Technology
NPS	Naval Postgraduate School
P-POD	Poly-Picosatellite Orbital Deployer
PARADIGM	Platform for Autonomous Rendezvous and Docking with Innovative GN&C Methods
PCB	Printed Circuit Board
P_{MAX}	Maximum Power Point
PV	Photovoltaic
RAM	Read-And-write Memory
RBF	Remove-Before-Flight
RTC	Real Time Clock
RTOS	Real-Time Operating System
SCAT	Solar Cell Array Tester
SERB	Space Experiments Review Board
SMS	Solar Cell Measurement System
SpaceX	Space Exploration Technologies Corporation

SSAG	Space Systems Academic Group
SSPL	Space Shuttle Payload Launcher
SSTL	Surrey Satellite Technology Limited
STK	Satellite Tool Kit
STP	Space Test Program
TASC	Triangular Advanced Solar Cell
TCS	Thermal Control Subsystem
TTL	Transistor-Transistor Logic
TVAC	Thermal Vacuum Chamber
UHF	Ultra High Frequency
UTJ	Ultra Triple Junction
VBAT	Battery Voltage
W	Watt

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I would like to thank my wife, Amy, for sticking around even though I told her I was getting out of the Navy in 2004. She has dealt with the numerous rigors that all Navy wives have dealt with throughout the existence of the Navy, even though she did not expect to. Amy has shown me nothing but love and patience the past 8 years, and has been the reason for my success in the Navy.

This thesis would not have been possible without the NPS-SCAT team, Commander Kerry Smith, LT Rod Jenkins, LT Cody Mortensen, Marissa Brummitt, Peter Reinhardt, Justin Jordan, and LT Jamie Fletcher. They have all performed above and beyond—thank you.

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I. INTRODUCTION

A. HISTORY OF THE CUBESAT

Small satellites have been around in one form or another since the beginning of mankind’s race to reach space. The very first manmade satellite, Sputnik, was a small satellite weighing just 83.6 kilograms (kg) and was just 58 centimeters (cm) in diameter. Although small satellites have been around for some time, the modern CubeSat got its start in 1999 [1]. It was conceptualized in collaboration between Stanford University and California Polytechnic State University. The concept was to teach students the necessary skills to develop, analyze and test satellites without having to invest a significant amount of funding. This would give the student hands on training in integration, launch, and satellite operations providing future space industry workers with some real world experience before getting out of college.

The first step was to develop a CubeSat standard, a standard that would not have overwhelming requirements and that would leave room for experimentation. The objective was to open doors for Universities that did not have the funding or experience to develop larger satellites. One important aspect that came out of the standards development was the Poly-Picosatellite Orbital Deployer (P-POD), a standard deployment system for CubeSats. This set the size and shape requirements for CubeSats, 10cm x 10cm x 10cm. See Figure 1 for examples of the P-POD and 1U–3U CubeSat structure.

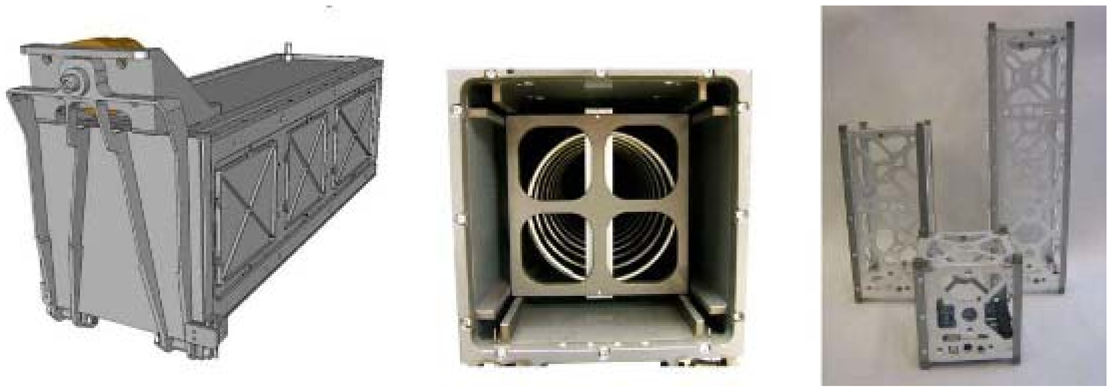

Figure 1. P-POD and Standard CubeSats (From [2])

The CubeSat is a modern concept, but as previously stated small satellites have a long lineage in space. In the last 50 years, 1578 satellites weighing less than 150 kg’s have been launched into space, of those 38 weigh less than 1kg [1]. The first CubeSat launch was June 30, 2003 from Plesetsk, Russia. A Eurokot launch vehicle took six CubeSats to Low Earth Orbit (LEO). Four of these were deployed from the P-POD and two from custom deployers. These CubeSats were developed by Japanese Universities and the University of Toronto. The first United States launch of a CubeSat was in 2006 with the launch of GeneSat – 1. At the time of this writing there have been 52 CubeSats launched, of those 34 have been successfully placed in orbit [2]. Two launch failures account for the 18 CubeSats that did not reach orbit [2].

These small satellites have moved from the university arena to the government and business arena. This is due to their ability to offer short development timelines, which translates to a shorter time to orbit. They are generally

low risk and cost less than larger satellites, this has caught the eye of the government and business communities. To date there are at least 53 companies, multiple government organizations, 50 U.S. and 41 foreign universities, located on six different continents, associated with the development, testing, launching, and operating of small satellites.

B. ADVANTAGES OF A CUBESAT

Small satellites offer numerous benefits to the space industry. As discussed above, the primary reason they have gained popularity over the last several decades is their cost and educational benefits. Modern large satellites are extremely expensive to develop, test, manufacture, launch and operate. In a recent 10-year forecast of satellite construction and launch markets from 2008 to 2019, the forecast predicts that the average satellite will cost approximately $99 million with an average weight of 4,166 pound (lbs) or 1,890 kg [3]. It also predicts launch costs of $51 million to launch these satellites [3]. This would equate to a launch cost of $12k/lbs or $27k/kg. These figures do not include secret military satellites. The price to build and launch a large satellite is prohibitive for many small companies and educational institutions, which are examples of organizations that would be best served by a less expensive alternative, such as small satellites.

Small satellites are defined by their weight. The company Surrey Satellite Technology Ltd. (SSTL) has been an innovator in small satellite design and has made efforts to standardize the industry, first by defining what constitutes a small satellite. A small satellite is defined by its

mass, weighing less than 500 kg. Further breakdown in the small satellite category has been made and there now exist numerous varieties of small satellites, which are also defined by their weight range. The categories are as follows: mini-satellites, 100-500 kg; micro-satellites, 10-100 kg; nano-satellites, 1-10 kg; and pico-satellites, those weighing under 1 kg [4]. The average launch cost for a CubeSat is between $30k and $40k per 1U. This, while still not cheap, is affordable for smaller institutions and increases access to space.

Small satellites not only save in launch costs, but also in the design and manufacturing process. The cost benefit is closely correlated to numerous other benefits. Simplicity is one of these benefits. While they are relatively less complex than larger satellites, they still have most, if not all, of the same subsystems of the larger satellites. Their small size lends itself to significantly decreased production time, which minimizes cost. The benefits of completing a small satellite in two years, vice ten years, will allow newer technologies to be put on orbit sooner [4]. The Joint Operationally Responsive Space Office (ORS) was established in 2007. While ORS is not building CubeSats, they have been able to cut the time from concept to launch down to five years with the smaller, faster approach. The TACSAT-3 project was given the go-ahead in 2004 and launched in 2009, a five year turn around [1], [5]. Small satellites offer an excellent platform for the testing of new technologies at a significant cost savings. NASA's NanoSail-D was launched on a SpaceX Falcon 1 rocket. Unfortunately, the Falcon 1 failed to achieve orbit. While this was a technical loss to NASA, in financial terms it was

a minor blip. NanoSail-D cost 2.3 million dollars, a miniscule amount of money in the world of satellites [6]. Small satellites, by nature of their size, cannot, as of yet, accommodate complex mission requirements. This means that their missions are fairly focused. With simpler mission objectives, smaller satellites can be designed less expensively, launched sooner, and provide less risk to their stakeholders [7].

In the event the satellite fails completely, stakeholders/sponsors are likely to suffer fewer consequences in contrast to the consequences suffered at the loss of a large satellite. With fewer consequences, investors are more willing to employ experimental technology for testing purposes in the hopes of advancing and improving their operations. This could allow these new technologies to be applied sooner to future satellites. Minimal complexity, combined with the implementation of newer technology, allows for greater automation of the operations process, minimizing manning, and allowing the cost of operations to be minimized as well. In summary, the cost savings allowed by small satellites can be categorized into these primary areas: design, integration, and testing, manufacturing, launch and satellite operations.

Small satellites do suffer from some disadvantages. A primary disadvantage is that their smaller size limits their ability to generate power. There is simply less volume in which to place batteries for power storage, and less surface area to employ solar panels for power conversion. This means they are less capable of accommodating design demands such as redundant systems, fine pointing requirements, onboard processing, and multiple payloads. The restrictions

on power also limit their communications data rates and subsequently their missions. It is a major reason why small satellites are well suited for simple mission tasking. However, there are singular missions that small satellites cannot currently accomplish as well as larger satellites. Imaging is a mission that is severely hindered by the satellite's small size. These small satellites have limits to the size of the payloads that can be placed on them. For example, the size of the imaging aperture that can be placed on a small satellite is smaller than what could fit on a larger satellite, and subsequently limits the obtainable resolution. Another aspect that is tied to the satellite's power limitations is the orbit the satellite is placed in. With minimal capability to generate power, signals transmitted to and from the satellites are limited in their range. Low Earth Orbit (LEO) is the primary orbit for small satellites due to this limitation. LEO has its own list of advantages, such as minimal range, and disadvantages, such as shortened lifetimes as compared with higher orbiting middle earth and geostationary/geosynchronous orbits. These advantages and disadvantages inherently belong to the satellites that reside there. As summarized by the Chairman and Director of SSTL, small satellite manufactures balance these advantages and disadvantages following the general principle of the 80/20 rule, 80% of the performance for 20% of the price [4][7].

C. THESIS OBJECTIVE

This is the third thesis to discuss the program management of designing, building, and testing a 1U CubeSat, the Naval Postgraduate School Solar Cell Array Tester (NPS-

SCAT) [8]. SCAT has been designed, built, and tested primarily by NPS students and interns from local colleges, with facilities and engineering support provided by NPS.

SCAT's primary payload is the Solar Cell Measurement System (SMS). The SMS was designed and built in house and will test four experimental solar cells for degradation in the LEO environment. A Sinclair Interplanetary Sun Sensor will be used in the SMS to collect sun angle data. Degradation will be determined by measuring Current vs. Voltage (I-V) curves, which, along with temperature and sun angle data, will be collected on orbit and analyzed at NPS. The VHF Beacon was built by students and staff Cal Poly, San Luis Obispo. The other subsystems are Commercial, Off-the-shelf, (COTS) technologies. See Table 1 for a list of COTS subsystems and manufacturer.

Subsystem	Manufacturer
Electric Power Subsystem (EPS)	Clyde Space
2.4 GHz S-Band Radio (Primary Communications)	Microhard MHX 2400
Command and Data Handling (CD&H)	**Pumpkin FM-430**
Structure	Pumpkin 1U CubeSat Kit

Table 1. Subsystems and Manufacturer

As will be documented in another student thesis [9], the SCAT Engineering Design Unit (EDU) to date has completed Thermal Vacuum (TVAC) and qualification vibration testing to NASA General Environmental Verification Standard (GEVS) +

6dB [10]. The flight unit build was begun in late August 2010. As of this writing, the flight and back up SMS units have been built, but have not been tested.

This thesis will also discuss the project's budget and schedule from December 2009 to September 2010. In addition, a total development cost estimate, including labor, equipment, and testing facilities, is determined. An overview of the satellite and subsystems will also be presented.

As program manager, the author was given the opportunity to take NPS-SCAT from an un-integrated EDU to a flight unit with a possible launch in mid-2011, sponsored by the Space Test Program (STP) on a launch vehicle that will be funded by the Operationally Responsive Space (ORS) Program. This thesis analyzes the issues with design, testing, integration, and qualification of the satellite, as well as providing the opportunity to evaluate the lessons learned by the design team for future implementation.

II. NAVAL POSTGRADUATE SCHOOL SOLAR CELL ARRAY TESTER

A. PROGRAM OBJECTIVES

The objective is to provide two 1U CubeSats (flight unit and backup) capable of operating and testing solar cells in LEO. While not specifically stated as a Key Performance Parameter (KPP), it was decided to build primary and back up flight units. This decision was based on the minimal cost that would be required for the increased reliability that having two flight units would achieve. The satellite must adhere to the CubeSat standard. The bus was designed using COTS to the maximum extent possible. All aspects of the design, assembly, integration, and testing have been captured for follow on projects. This ensures that once a qualified structure and bus have been completed, new payloads may be integrated for future projects using a standard NPS 1U bus. See Table 2 for a list of the NPS-SCAT KPPs [11].

KPP Number	KPP
001	*The satellite development program shall provide NPS students with an education in the satellite design process, integration, testing, and full life cycle of a space flight system.*
002	*The satellite shall utilize a 1U Pumpkin© CubeSat architecture and Commercial Off the Shelf (COTS) hardware whenever possible.*
003	*The solar measurement system shall be capable of obtaining solar cell I-V data curve to include solar cell current, voltage, temperature, and sun angle no less than once per orbit.*
004	*The satellite shall be able to communicate Telemetry, Tracking and Command (TT&C) and Payload data to the NPS ground station using an S-band radio (primary transmitter) and/or UHF beacon (secondary transmitter).*
005	*The satellite shall transmit TT&C and Payload data regularly (aka "in the blind") via the UHF beacon and transmit data when a communications link is established with the ground station via the S-band radio.*
006	*The satellite shall be capable of being launched via a CubeSat standard compatible deployer (like a P-POD) on an Evolved Expendable Launch Vehicle (EELV).*
007	*The satellite shall operate continuously in orbit upon launch and have a mission life of 1 year.*
008	*The satellite development program shall establish the CubeSat program at NPS by creating a CubeSat working group, small satellite process and procedure development, and establishing an engineering support structure.*

Table 2. NPS-SCAT Key Performance Parameters

During the past year, the NPS-SCAT program has been a platform for students to gain valuable experience in satellite design, integration, testing and operations. Students were involved in every aspect of the project as

program and subsystem managers. Significant student experience was gained in program management, communication subsystems, payload system design, electrical subsystem design, vibration testing, thermal vacuum testing, and software engineering. Figure 2 shows an organizational chart of the 2010 NPS-SCAT team.

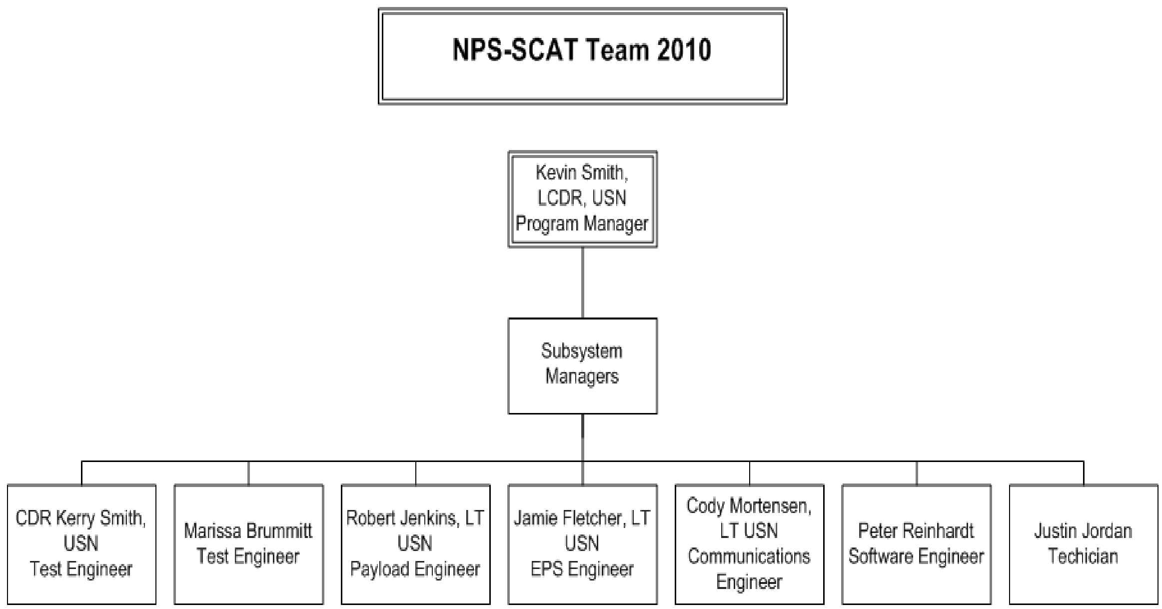

Figure 2. 2010 NPS-SCAT Team

B. NPS-SCAT SUBSYSTEMS

1. Payload

The payload for the NPS-SCAT is the SMS. It consists of three major components; the SMS circuit board, the Experimental Solar Panel (ESP), and the sun sensor. These three sub-systems had to be designed, or procured, and integrated into the space of a 1U CubeSat, while leaving room for the other subsystems. This presented some design challenges for the student in charge of the payload design [2].

a. *Solar Cell Measurement System*

In designing the SMS circuit board, many considerations had to be taken into account. Space in a 1U CubeSat is at a premium, this would affect how the sun sensor could be mounted. This in turn affected the layout of the board circuitry itself [2].

Three different designs were considered. In the end, the final design was the simplest [2]. For a complete analysis of SMS trade space, see [2]. The design placed the sun sensor in the middle of the SMS circuit board, allowing the experimental solar cells to be placed around the perimeter of the SMS board. Throughout the design process, several iterations of the SMS were made. The board evolved from a bread board with jumpers, to one with surface mounted components, referred to hereafter as SMS Version 3, and shown in Figure 3 The SMS payload processes Current-Voltage (I-V) curve data from four different experimental solar cells, temperature sensors co-located with the experimental solar cells, and sun angle for analysis of solar cell performance in the LEO environment [2].

Figure 3. Version 3 of the SMS

b. Experimental Solar Panel

As with the SMS circuit board, the Experimental Solar Panel (EPS) board development dealt with issues of space. The ESP acts as the +z-axis face of the satellite. Figure 4 shows NPS-SCAT axes orientation. It must accommodate a hole in the center for the aperture of the sun sensor. It also has to fit four experimental solar panels and their individual temperature sensors [2].

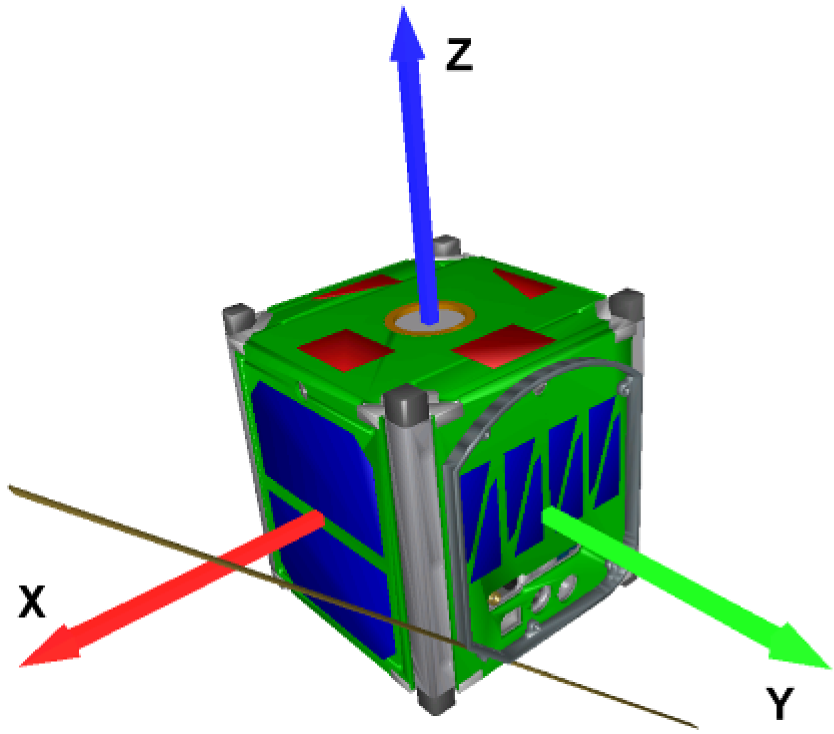

Figure 4. NPS-SCAT Axes (From [12])

The four NPS-SCAT cells that were chosen to be tested include:

- Spectrolab Triangular Advanced Solar Cell (TASC), an Ultra Triple Junction Cell (UTJ) [13]
- Spectrolab Improved Triple Junction (ITJ)[14]
- EMCORE Triple Junction with Monolithic Diode Solar Cell (BTJM) [15]
- Polycrystalline, [16]

The EMCORE cells were chosen due to the fact they were given to the NPS-SCAT program free of charge. The Spectrolab were chosen, since they have cover glass and are a good comparison to the EMCORE cells, which do not have cover glass. The polycrystalline are flown frequently by the United States Naval Academy, but I-V curve data has never

been obtained. The TASC cells are also frequently used in space applications, therefore, TASC I-V will be useful to future space flight operations.

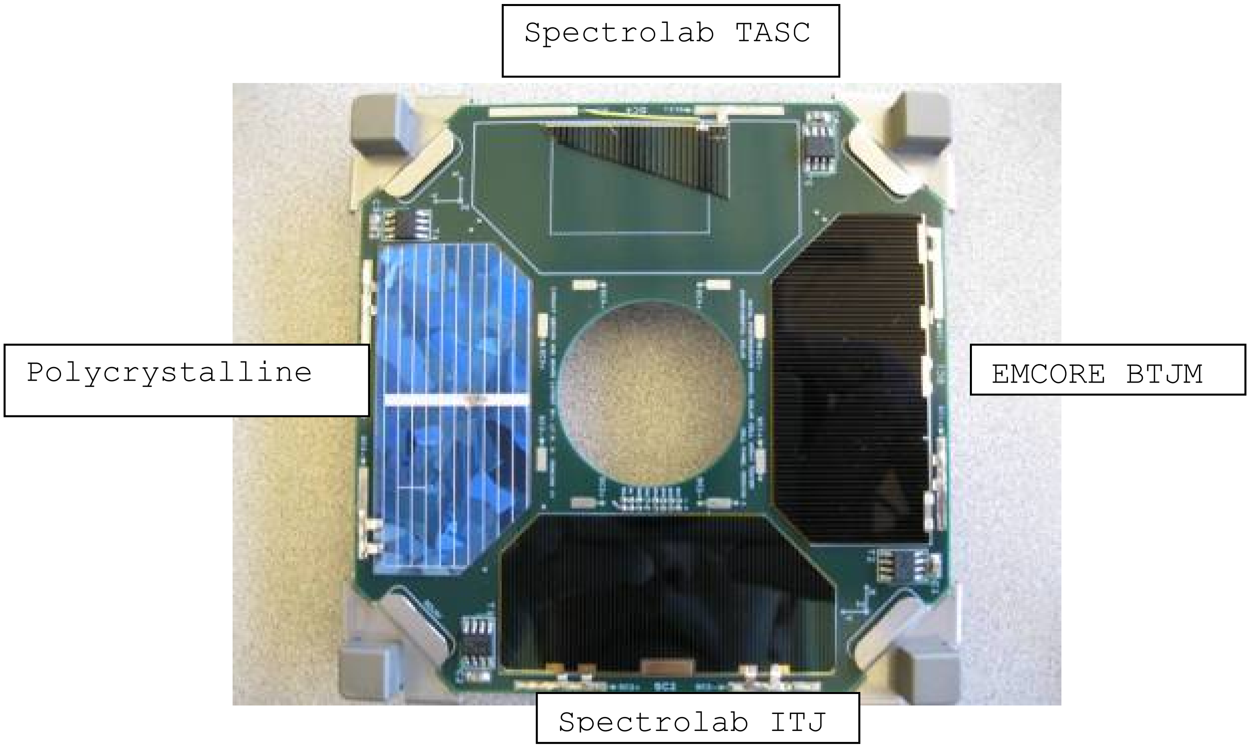

Figure 5. Version 3 of ESP showing the 4 experimental solar panels

The ITJ, ATJ, and polycrystalline solar cells are fabricated in sizes too large to fit on the ESP. As stated in [17], NPS-SCAT solar cells are very difficult to cut by traditional glass cutting methods. When final solar cells were selected, they had to be cut to size, and it was decided to look for an external means to have them cut. Of the four experimental cells, only three had to be cut, since the TASC cell was already in a form factor that fit the ESP design. Figure 5 shows the flight configuration of the ESP with experimental solar cells.

Op Tek System was chosen for the job. Op Tek is a supplier of laser processing tools and sub-contract machining services. Two representatives from the company met with the author and the ESP designer to discuss the options for cutting the solar cells. Op Tek would fabricate jigs and laser cut the cells to the desired shape. The Op Tek representatives did express concern that the cells would not work once they had been cut, since they would be cutting into the active part of the solar cells. Figure 6 shows an uncut ITJ cell. This was of particular concern for the ITJ and ATJ cells since they are multilayer cells. As shown in Figure 7, the outline of the area to be cut is in the power producing are of the solar cell.

After the meeting with Op Tek, the advantages and disadvantages were discussed with the team. It was decided that even with the risk of the cells not working after they were cut, the cells would be cut by Op Tek. Enough cells would be cut to make the flight unit and backup. The total cost for having the solar cells cut was $2700.

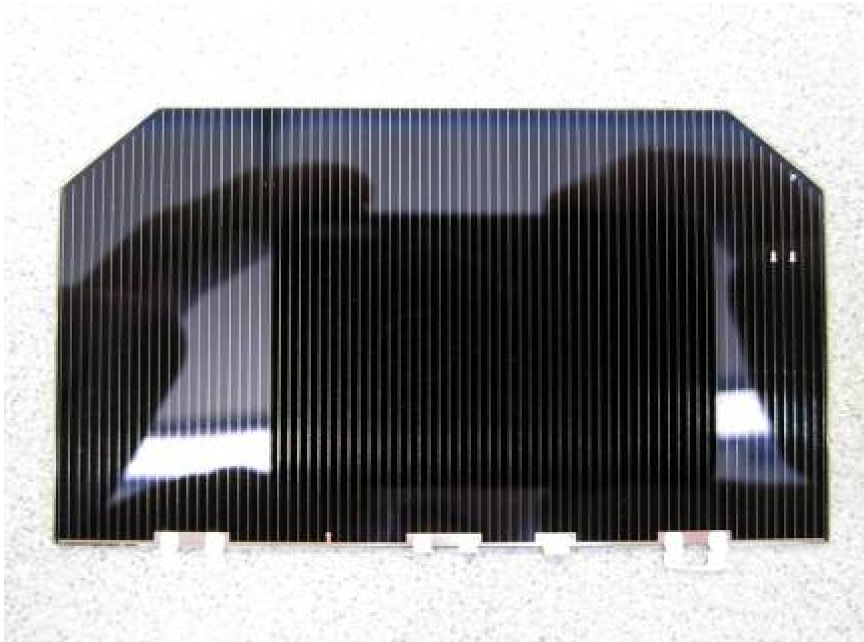

Figure 6.   Shows an uncut ITJ cell

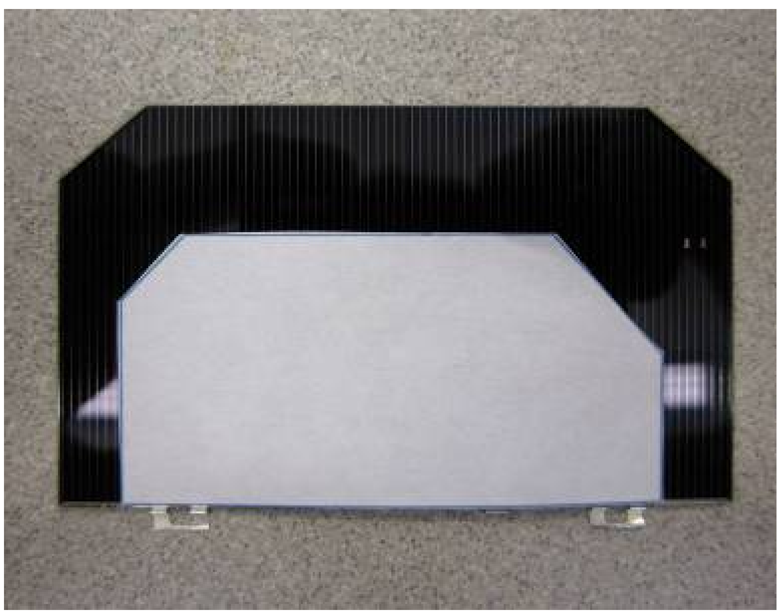

Figure 7.   Uncut ITJ with outline showing the area of cell that will need to be cut to fit on the ESP

It took Op Tek approximately one month to complete the solar cell cutting. The cells were tested immediately upon arrival in the lab and both the ATJ and ITJ cells were indeed shorted. To help understand what happened, it will be useful to take a look at the construction of multi-junction solar cells. For the purposes of this thesis, only an overview of the construction will be looked at. For a more detailed analysis, see [18].

Multi-junction cells are constructed with stacked layers. Each layer is designed to capture different wavelengths of light to improve the efficiency of the solar cell. Three of the cells that are being tested on NPS-SCAT are multi-junction cells. Figure 8 shows a cross section of the Spectrolab ATJ solar cell [18].

At the top and bottom of the solar cell, there are contacts that are used to draw off the current generated by the cell. Figure 9 shows a close-up of a multi-junction solar cell. The red arrows are pointing toward the contacts; each line in the top layer is a contact. The top contact covers approximately 2–8% [18] of the cell, and should not be confused with the solder tabs used to connect the cells electrically. The bottom layer contact is one solid layer.

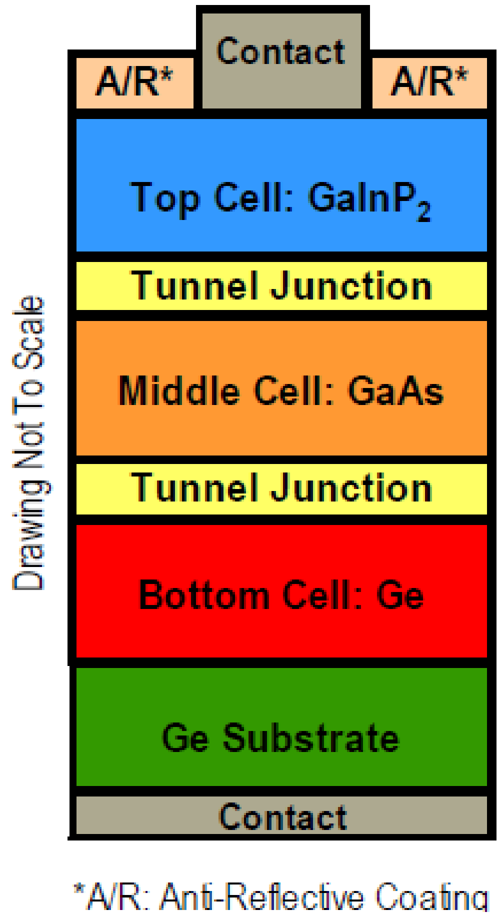

Figure 8. Cross Section the Spectrolab UTJ Solar Cell (From[13])

The middle layers are the actual current-producing layers. The light passes through these areas, exciting electrons, and causing current flow. The current is then drawn off via the contacts.

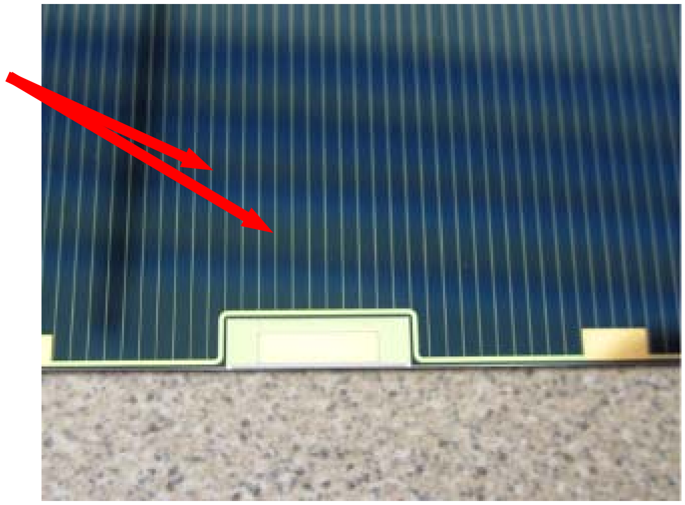

Figure 9. A close up image of a solar cell showing the contacts, the red arrows point to the contacts

Knowing the basics of the cell construction, and the fact that the cells were cut with lasers, the most likely cause for the solar cells not working is that some or all these layers were melted together during the cutting process, causing a short circuit across the layers.

It was decided to try and use a polishing compound to rub the edges of the cells to “clean” off the layer of material shorting the cell. While researching the correct polishing compound, a team member suggested that 2000 grit wet/dry sandpaper, which is used in automotive finish painting, would be worth investigating. This was discussed among the team members, and it was determined to be a valid course of action, and the sandpaper was inexpensive compared to the carbide polishing compounds that were being researched. The sanding did indeed work. The following content is a comparison of the cells before

and after “cleaning” with sandpaper. The cells are shown here through a magnifying glass. Figure 10 shows the pre-sanded cell.

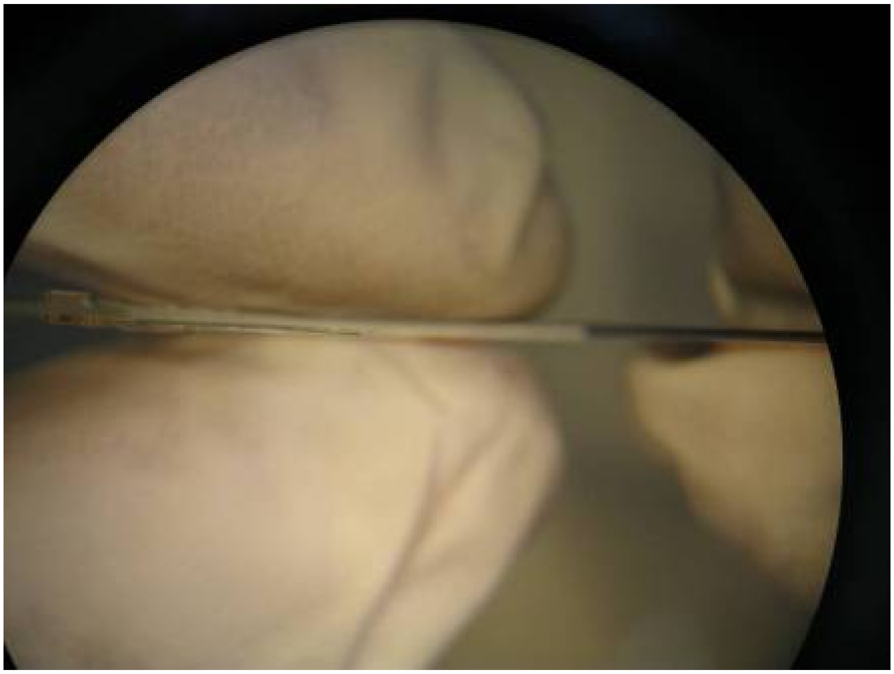

Figure 10. Pre sanded solar cell, notice the absence of discernable layers

The 2000 grit wet/dry sandpaper was purchased at a local automotive supply store. In this instance, the sandpaper was used wet. In order to sand the cells, first one had to hold the cell as level as possible and then slide the cell along the paper, on a flat surface, in one direction. To prevent recontamination, the cell would be moved to a clean part of the sandpaper once an area became saturated with debris. Each cell took approximately 15-20 minutes to complete. Figure 11 shows the sanding process.

Figure 11. Sanding the solar cells on 2000 grit wet/dry sandpaper

After the cells were sanded, they were tested with a MASTECH MY64 multi-meter. The cells were no longer shorted and produced the correct voltage for each particular cell. Figure 12 shows the post sanded cell.

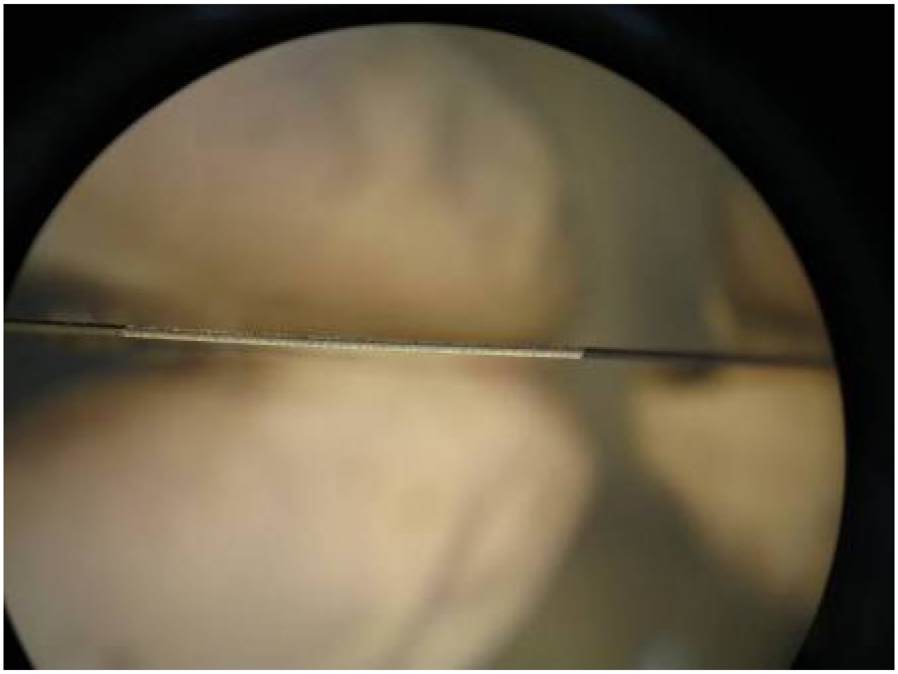

Figure 12. Post sanding cell, individual layers can now be seen

The cells were then attached to the ESP board and a functional test of the SMS system was conducted. I-V curves were produced as expected.

2. Electrical Power System

a. EPS Board

The EPS for NPS-SCAT is the Clyde Space 1U power system. The EPS consists of two components, the EPS board and the battery daughter board. The EPS that will be used on the flight unit of NPS-SCAT is the second version of the 1U Clyde Space EPS, see Figure 13. While the Engineering Design Unit (EDU) was built and tested with Version-1, it was decided to switch to Version-2 for the flight unit. This is due to the parasitic load problem with Version-1 of the

EPS. While in the launch configuration (pull pin pulled out and the separation switch depressed), there is a ~1 mA draw on the battery. With the pull pin out, the battery is connected to the battery charge regulators, but not to the 5 volt or 3.3 volt regulators. Depressing the separation switch isolates the EPS from the EPS voltage regulators. Ideally there would be no current draw in this configuration. This current draw was not acceptable to the team, as once the satellite is integrated, there is no way of maintaining or monitoring the battery state. A month or more of such a drain, as would be expected after integration into the P-POD, would cause a deep discharge of the battery, resulting in a shorter battery life and lower battery efficiency.

Clyde Space offered two fixes to the parasitic load problem. One was a jumper solution to bypass the affected circuitry and the other was to purchase the new version of their EPS. It was decided that the program budget could afford the new EPS and it was purchased for the flight unit. If the backup unit is flown, it will either fly with the first version Clyde Space EPS or a different EPS all together, possibly a GomSpace 1U EPS.

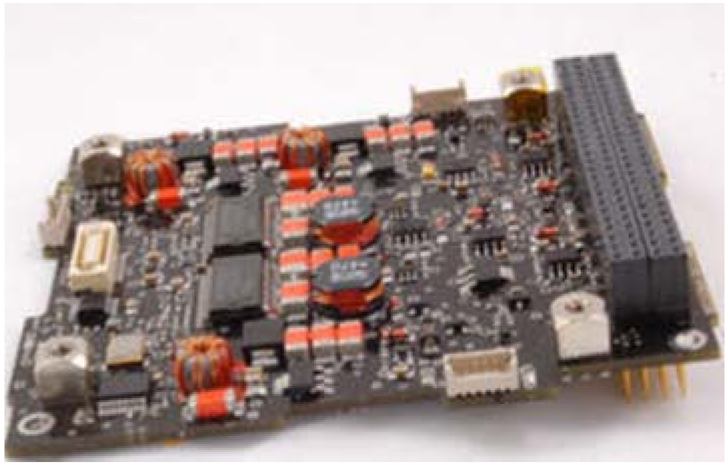

Figure 13. Clyde Space 1U EPS

The EPS has two operating buses at 5.0V (volts) and 3.3V. The battery has an operating output voltage from 6.2V to 8.26V, with a maximum operating current of 0.5A [19]. The EPS communications protocol is I^2C. Clyde Space provides two means of protection for the EPS, over-current and battery under-voltage. The over-current protection is present on all buses. A fault condition is monitored and the protection will be reset when the fault condition clears. The battery under-voltage protection will shut off power to all loads, and begins to charge the battery immediately, as long as at least one solar panel is illuminated. Power will not be supplied until the battery has been charged sufficiently to greater than about 7V. Table 3 shows the trip points for the protection circuits [19].

Protection	Trip	Reset
Over-Current	5.0V bus………2.956A 3.3V bus………2.8A	When over-current condition is cleared
Battery Under-Voltage	Battery Voltage <~6.2V	Battery Voltage > ~7V

Table 3. Clyde Space 1U Power Supply Trip Points and Resets

b. Battery Daughter Board

The battery daughter board has two Lithium Ion Polymer battery cells connected in series. The board is capable of providing battery voltage, current and temperature telemetry for health and status of the battery for each cell. To maintain cell temperature, a battery heater is provided. Battery over current protection is also provided. The battery daughter board is capable of operating at a maximum voltage of 8.26 volts with a corresponding capacity of 1.25 amp hours [19]. Figure 14 shows the Clyde Space battery daughter board.

Figure 14. Clyde Space Lithium Ion Polymer Battery Daughter Board

c. On Orbit Power

On orbit power will be provided by a combination of Spectrolab TASC and ITJ solar cells. Five faces on the satellite will have power generating cells. Figure 15 shows the different power generating faces. The experimental cells will not be used for power generation. Two of the five faces, the +y-axis and –z-axis, will have a combination of eight TASC cells arranged on them. The other three faces will have two ITJ solar panels each. Using [20], an analysis of solar cell power generation was accomplished. The average power generated during each orbit was 0.648W. This is representative of the possible orbital parameters for SCAT. The final orbital parameters for SCAT have not been set, but are expected to be between 350 km and 550 km in altitude with an inclination of 45 degrees. The average power was derived from Satellite Tool Kit (STK) simulation with the following parameters [20].

- Orbit Altitude = 410 kilometers
- Orbit Inclination = 51.6 degrees
- Orbit time = 92.77 minutes
- Maximum Eclipse Time = 36.0 minutes
- Tumble Rate = 0.03 revolutions/minutes.

When the orbital parameters for SCAT are set, another analysis should be conducted to determine more accurate power generation data.

Figure 15. -Z-Axis, +Y-Axis, and one of the ITJ Power Generating Solar Panels

d. *Clyde Space Flight Heritage*

Operator	Satellite	Launch Date	Operational (In Orbit Transmitting Data)	Orbit (km) Perigee x Apogee x Inclination
Istanbul Technical University	ITUpSAT1	September 23, 2009	Yes	720 x 98.28°
Hawk Institute for Space Sciences	HawkSat-1	May 19, 2009	No*	432 x 467 x 40.5°
University of Texas at Austin	Paradigm/BEVO1	July 30, 2009	No	343 x 351 x 51.64°

Table 4. Clyde Space Know Flight Heritage (From [21], [22])
*In orbit, it is unknown if it is transmitting data

There are eight more expected flights of Clyde Space EPS products in the relatively near future, based on sales to-date of EPS systems. NPS-SCAT is included [21].

3. Communications

The communications subsystem on NPS-SCAT will consist of primary and secondary systems. The primary means of communications will be the Microhard Systems Inc. MHX 2400, a 2.4 GHz COTS wireless transceiver. The secondary communications system will be a Cal Poly-developed, 438 Megahertz (MHz) transceiver. While a summary is provided below, details are included in another student thesis [23].

Both transceivers will have ground stations on campus at NPS. The ground stations will be operated by student and faculty of the school. The 438 MHz beacon is a public communications tool. It will transmit telemetry as well as experiment data at regularly spaced intervals. It will also transmit a “Hello World” equivalent transmission at regularly spaced intervals. It will be available to the amateur radio users around the world. Although the details have yet to be worked out, it is expected that data received by amateurs from the beacon will be collected by NPS students and staff. It is currently being discussed how to get this information back to NPS. E-mail, or the NPS-SCAT website, are currently options available.

Both frequencies will be licensed using an Amateur Satellite Frequency Coordination Request (ASFCR). Since both are amateur frequencies, they cannot be licensed to a government agency. The license request was sent through the NPS Amateur Radio Club, K6NPS.

a. Microhard Systems Inc. MHX 2400

The MHX 2400, shown Figure 16, is paired with a Spectrum Controls Inc. patch antenna. The antenna will be mounted on the −z face of the satellite. Technical specifications are for the MHX 2400 and antenna are provided in Table 5. The Microhard MHX 2400 has flown on at least three previous 3U CubeSats, GeneSat, MAST [24], and PHARMASAT [25].

Figure 16. MHX 2400 (left) and Patch Antenna (right)

MHX 2400 Technical Specifications	
Band	Industrial, Scientific, and Medical (ISM)
Frequency	2.4 Gigahertz (GHz)
Data Rate	9.6 kilobits/second (kbps) Up/Down
Power Out	~1 Watt
Mean Power Consumption	~2 Watts
Receive and Transmit Power Consumption	~4.8 Watts
Half Center Frequency (Antenna)	2.45 GHz
Bandwidth (Antenna)	120 MHz
Polarization (Antenna)	Left or Right Hand Circular
Standing Wave Ratio	2:1

Table 5. MHX 2400 and Patch Antenna Technical Specifications (From [23])

b. 435 MHz Transceiver (Beacon)

The beacon transceiver, shown in Figure 17, is a Cal Poly built communications system. It is constructed to the PC-104 form factor but is compatible with the CubeSat Kit. The transceiver is a Chipcon CC100 using the AX.25 protocol. The communications controller supports I^2C to communicate with the satellite bus. The beacon is paired

with a half-wave dipole antenna. The transceiver and antenna technical specifications are listed in Table 6.

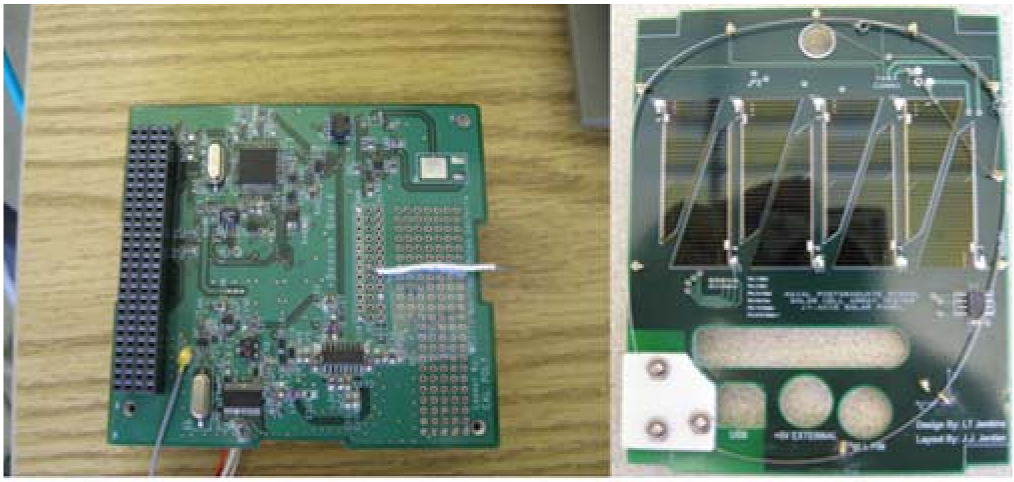

Figure 17. Cal Poly Beacon and +Y Face with the Beacon Antenna (Stowed Position)

Beacon Transceiver Technical Specifications	
Band	Amateur
Frequency	438 MHz
Data Rate	600 Baud Uplink, 1200 Baud Downlink
Power Out	~1 Watt
Transmit Power Consumption	~2 Watts
Receive Power Consumption	~0.1 Watts
Half Center Frequency (Antenna)	438 MHz
Length (Antenna)	32 centimeters (cm)

Table 6. Beacon Transceiver Technical Specifications (From [23])

4. Command and Data Handling

Command and data handling will be via the Pumpkin FM430, shown in Figure 18. It uses a MSP430, 16-bit microcontroller running the Salvo Real Time Operating System (RTOS). On board storage will be on a 1-gigabyte SD card [26].

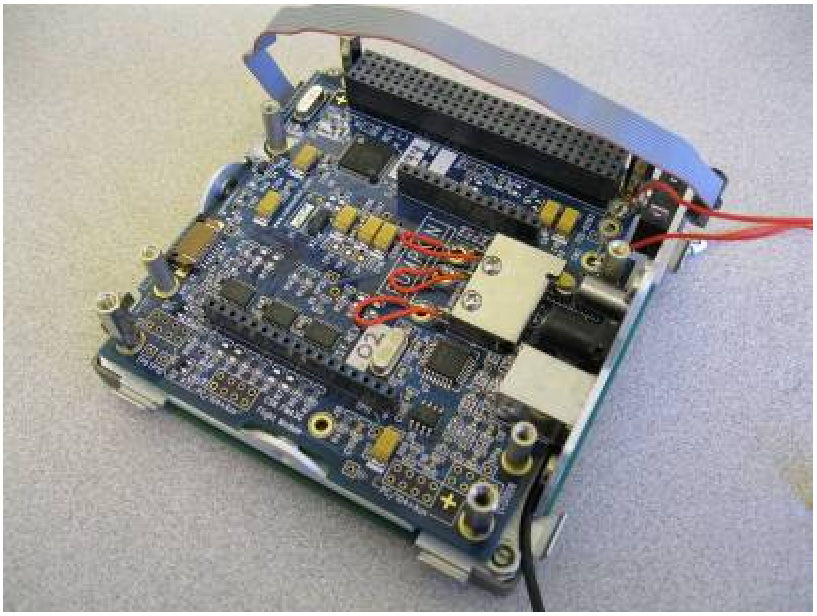

Figure 18. Pumpkin FM430

5. Structure

The structure is another COTS product produced by Pumpkin Inc. Figure 19 shows a 1U skeletonized structure. The structure is available in solid or skeletonized configurations. For NPS-SCAT, we used a combination of both. The +z and –z face of the satellite are solid structure and the rest are skeletonized. The skeletonized structure is made of aluminum and comes ready for integration with screws and fasteners.

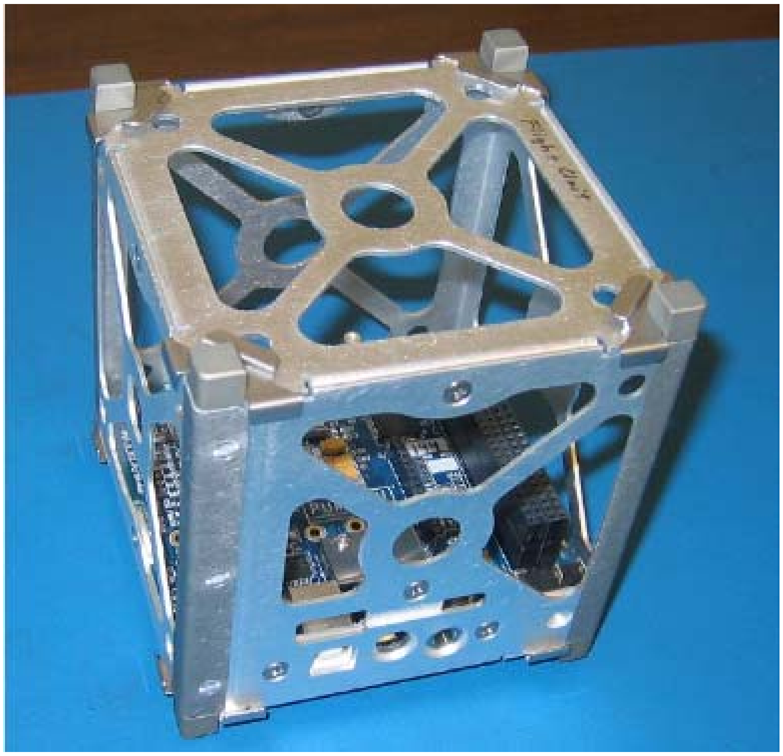

Figure 19. U Skeletonized Structure

Modifications had to be made to the +z and –z faces for NPS-SCAT. Figure 20 shows the modified +z and –z faces. This was done to accommodate the sun sensor and the antenna for the S-Band radio. All modifications to the structure were reviewed by the team, and all the work was done by the SSAG machinist.

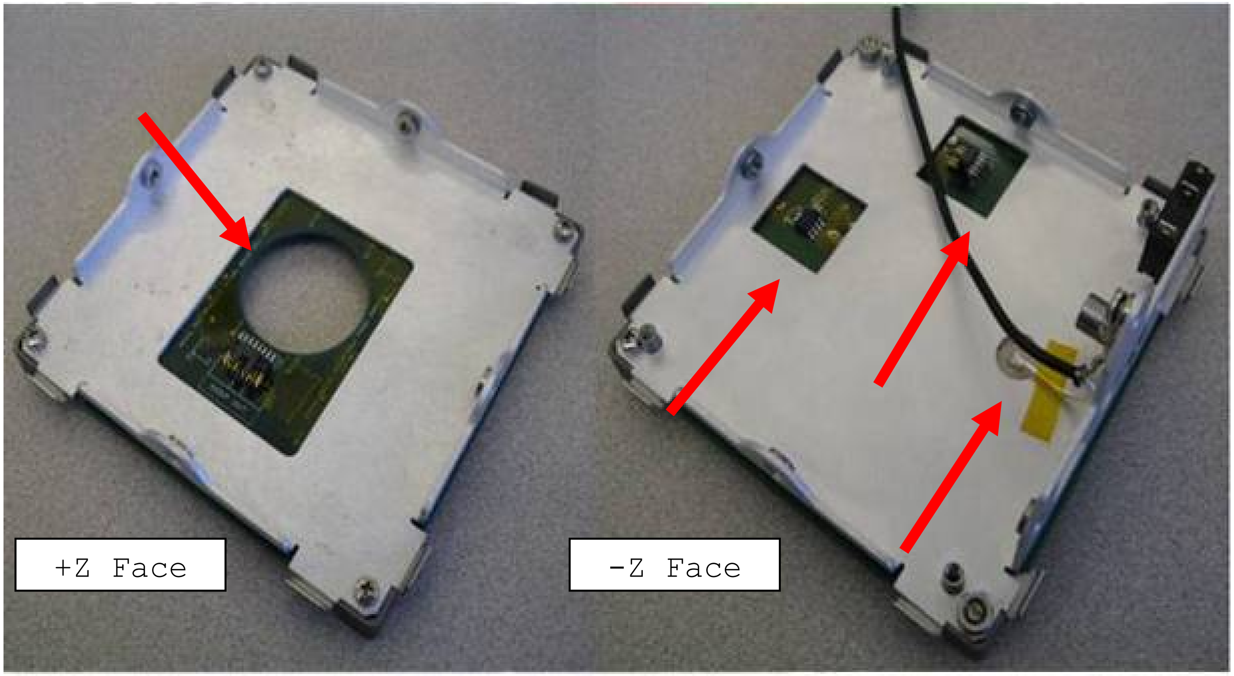

Figure 20. +Z and −Z Faces, the Red Arrows Point to Areas that were Modified

a. *Pumpkin Inc. Flight Heritage*

In 2000, Pumpkin Inc. began selling CubeSat kits. Since then, many have made it to space. Table 7 shows the space heritage of Pumpkin equipment.

Satellite	Pumpkin Equipment Flown	Launch Date	Operational (In Orbit Transmitting Data)	Orbit (km) Perigee x Apogee x Inclination
ITUpSAT1	FM430, 1U Structure	Sept 23, 2009	Yes	720 x 98.28°
HawkSat-1	FM-430, 1U Structure	May 19, 2009	No*	432 x 467 x 40.5°
AIS Pathfinder 2	FM-430	Sept 23, 2009	Yes	720 x 90°
Delfi-C3	FM-430, 3U Structure	April 28, 2008	Yes	642 x 621 x 97°
MAST	3U Structure, Salvo Pro RTOS v3.2.3	April 17, 2007	Yes	647 x 783 x 98°
Libertad-1	FM-430, 1U Structure, Salvo Pro 4 RTOS	April 17, 2007	Yes**	660 X 98°

Table 7. Pumpkin Inc Equipment Flight Heritage (From [27], [28], [29], [30], [31]) *In orbit, it is unknown if it is transmitting data **No longer operational, completed mission

6. Concept of Operations

The NPS-SCAT concept of operations can be broken into two major types of operations, Command Actions (CA) and Autonomous Actions (AA). Each task will check Battery Voltage (VBAT) to ensure there is sufficient power available to complete the operation. If not, the operation will be cancelled or delayed. The software, once compiled on the ground and loaded into the satellite cannot be changed [32].

a. Command Actions

As suggested, CAs are driven by commands from the ground, commands can be sent via the MHX 2400 or the Beacon. These can be used by ground operators to get telemetry data from satellite systems, command the radios to be powered off or on, or gather experiment data. For a complete list of available CAs, see the Appendix.

b. Autonomous Actions

Autonomous Actions can further be broken down into startup actions, interrupt driven actions and timer driven actions. After separation from the CubeSat launcher, the FM430 will commence startup actions. It will turn off the SMS, Beacon, and MHX-2400 to conserve power. A 30-minute delay will then begin to allow sufficient separation distance from the primary payload. This will ensure the primary payload is not affected by the secondary payloads. Startup actions will be completed after every reset, the 30-minute timer will only be executed on the initial startup. After the 30-minute delay, a timestamp is collected, and the FM430 checks the status of the Beacon antenna deployment.

If it is not deployed, an attempt is made to deploy it. Beacon deployment actions are discussed below. At this time in the startup sequence, the scheduler becomes active, all tasks become eligible to run, and normal operations begin. Figure 21 shows a diagram of the startup actions [32].

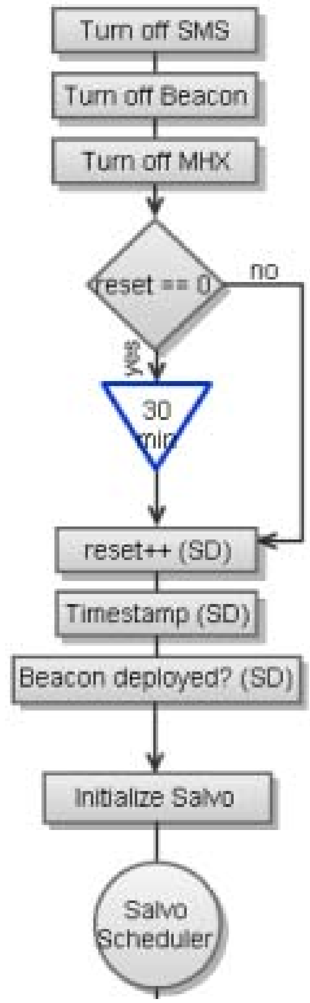

Figure 21. Diagram of Start Actions (From [33])

The deployment of the Beacon antenna is a separate action from the startup actions. Prior to the beacon antenna being deployed, the battery voltage (VBAT) must be greater than 8V. If VBAT is less than 8V, the action will be delayed and VBAT will be checked on a predetermined time

interval. This limit was placed on VBAT to ensure that enough power is available to deploy the beacon antenna. If more than five attempts are made to deploy the antenna, and the beacon is still not deployed, this action will be delayed indefinitely. The deployment mechanism consists of three resistors wired in parallel connected to Nichrome wire. As power is applied to the resistors, the Nichrome wire heats up and it melts the fishing line that holds the antenna in the stowed position [32]. The total resistance of the circuit is ~4 ohms, this is includes the resistance of the Nichrome wire. The approximate time to burn through the fishing line is ~3 seconds. Energy, in Amp-Hours, (Ahr) used by the deployment circuit for each attempt is given by two equations 2.1 and 2.2.

$$i = \frac{8v}{4omhs} = 2amps \tag{2.1}$$

$$Ahr = 2amp \times 8.3e^{-4}hr = 0.0016Ahr \tag{2.2}$$

The amount of energy used by the circuit during attempt to deploy the antenna is small compared to the overall capacity of the battery, 1.25 Ahr. Figure 22 shows a diagram of the beacon deployment actions.

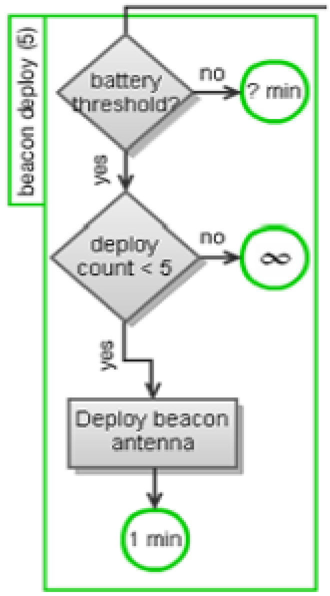

Figure 22. Diagram of Beacon Deployment Actions (From [33])

Interrupt driven actions are MHX Receive, MHX Transmit, and the Beacon Receive. When the satellite is passing over the ground station in Monterey, CA, the MHX on the satellite will handshake with the MHX 2400 in the ground station. This will cause the MHX Transmit action to be eligible to run. This action will attempt to download all data that has not been previously transmitted [32].

The MHX Receive action is driven by the reception of a command via the MHX that requires processing. Prior to processing the command, VBAT is checked to ensure there is sufficient power to complete the action. Once the command is processed, the action is delayed until the receipt of new command. The Beacon Receive action acts in the same way, but via a command received on the Beacon. Both of these actions share the same process command task used to process the incoming data. Figure 23 shows a diagram of the interrupt driven actions [32].

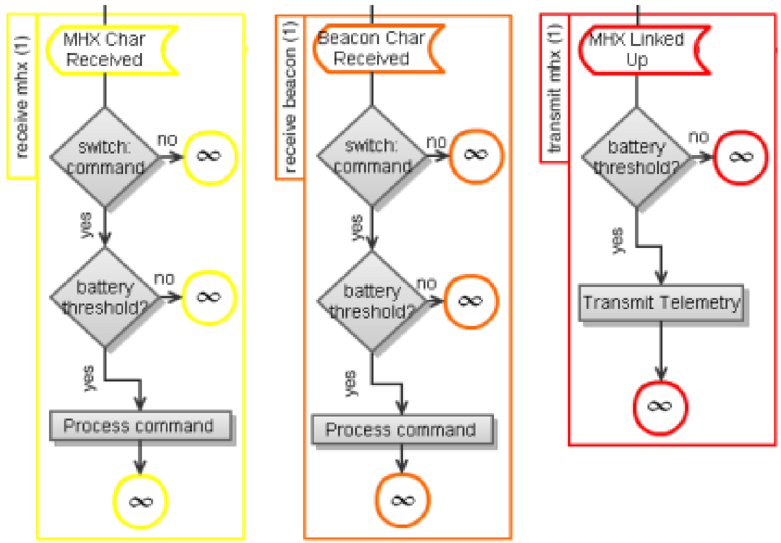

Figure 23. Diagram of Interrupt Driven Action (From [33])

The timer driven actions are MHX Wakeup, Beacon Blip, Beacon Transmit, and Data Collect. See Figure 24 for a diagram of these actions. The MHX Wakeup action turns on the MHX radio every 2 minutes for 10 seconds. This allows the radio to try to handshake with the ground station. If the handshake occurs, the radio is kept on for an additional 3 minutes to receive commands or transmit data. After the handshake is terminated the radio will be shut off for 85 minutes until its next possible pass over the ground station. This will allow for better power management throughout the orbit if only a single S-band ground station is available [32].

The Beacon Transmit and Blip functions are contained on the same timer driven action that will transmit data on predetermined intervals. The blip action will transmit a message every 30 seconds, saying this is NPS-SCAT. The Transmit action will transmit the latest data at

5-minute intervals. After the transmit action is complete, the 30 second timer for the beacon blip will start again [32].

The last action is the Data Collect action. At a minimum, this action will collect a timestamp, temperature, and battery state. If the +z-axis is in the sun, the SMS will be turned on to collect an I-V curve and sun angle data. If the sun sensor is not in the sun, another timestamp will be taken, and the SMS will be turned off. Data collected will be saved to the SD card with a unique identifier that can be requested by the ground station, if desired. This task will be delayed for 10-15 minutes until it is eligible to run again [32].

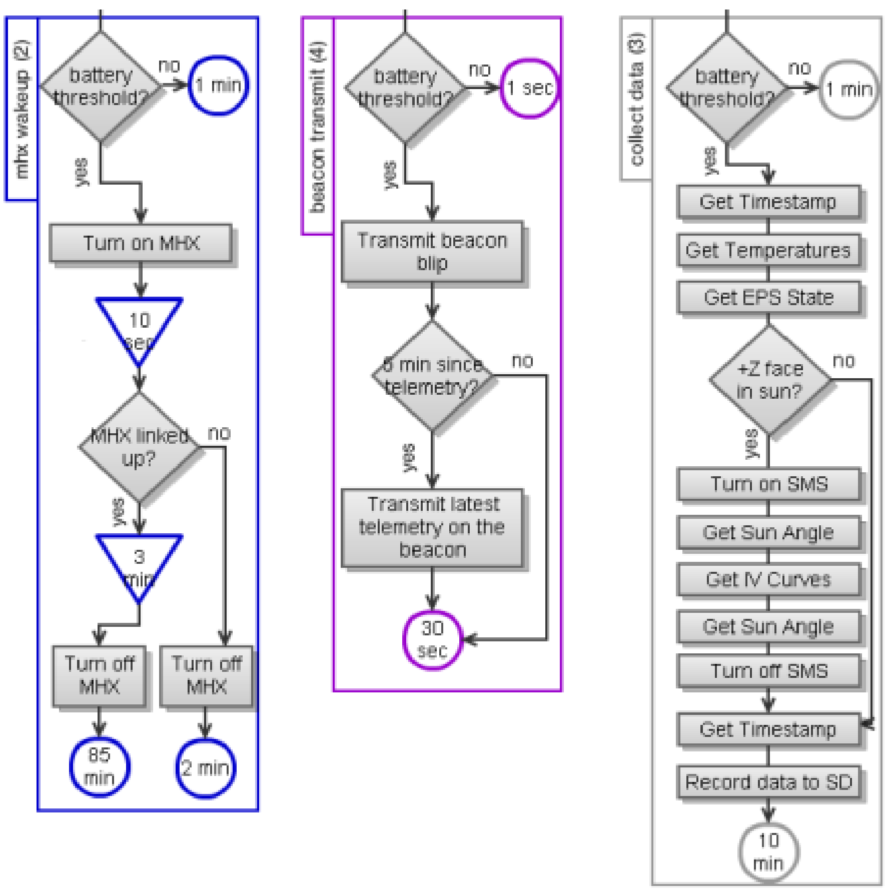

Figure 24. Diagram of Timer Driven Actions (From [33])

The software, to date, is not a 100% solution, and will continue to undergo review and revision. Currently the software engineer is trying to resolve an issue with Random Access Memory (RAM) allocation when saving data to the SD card. This is causing a large amount of RAM to be used, thus limiting the number of processes that can be run by the FM-430. Our Software Engineer and a faculty member are working with Pumpkin Inc. to find a solution to this problem. A complete CONOPS diagram is shown in Appendix L.

III. PROGRAM MANAGEMENT

A. PROGRAM MANAGEMENT

There was a great deal of experience gained in the management and the execution of funds for this project. The Program Manager responsibilities included full budget authority and the program schedule. The author also assisted the other subsystem managers when needed. The budget for FY 2010 was $69k for equipment, labor, indirect cost, contracts, and travel. A detailed budget analysis will be discussed later.

One design issue with a monetary impact that had to be resolved was the deployment mechanism for the VHF Beacon antenna. The antenna deployment mechanism was integrated on the +y-axis board of the satellite. Therefore, each design iteration of the antenna would in turn cause a redesign of the +y-axis board. In this instance, the program spent approximately $850.00 on Version-2 of the +y-axis board to accommodate the new antenna deployment design. Once the new +y-axis board arrived, it was discovered that the antenna, while in its stowed position, would not be within the tolerances of the CubeSat standard. This would cause a problem with the satellite's fit in the P-POD. Another version of the +y-axis was required to fix this design flaw. In Figure 25, the two red arrows point the areas where the antenna extends beyond the board, and therefore, violates the CubeSat standard. Although the antenna does not extend very far past the boundary of the board, this may cause the antenna to rub against the rails of the P-POD causing damage

or a malfunction during launch and/or deployment. Strict adherence to standards is important, and constant reviews are required to ensure that standards are complied with.

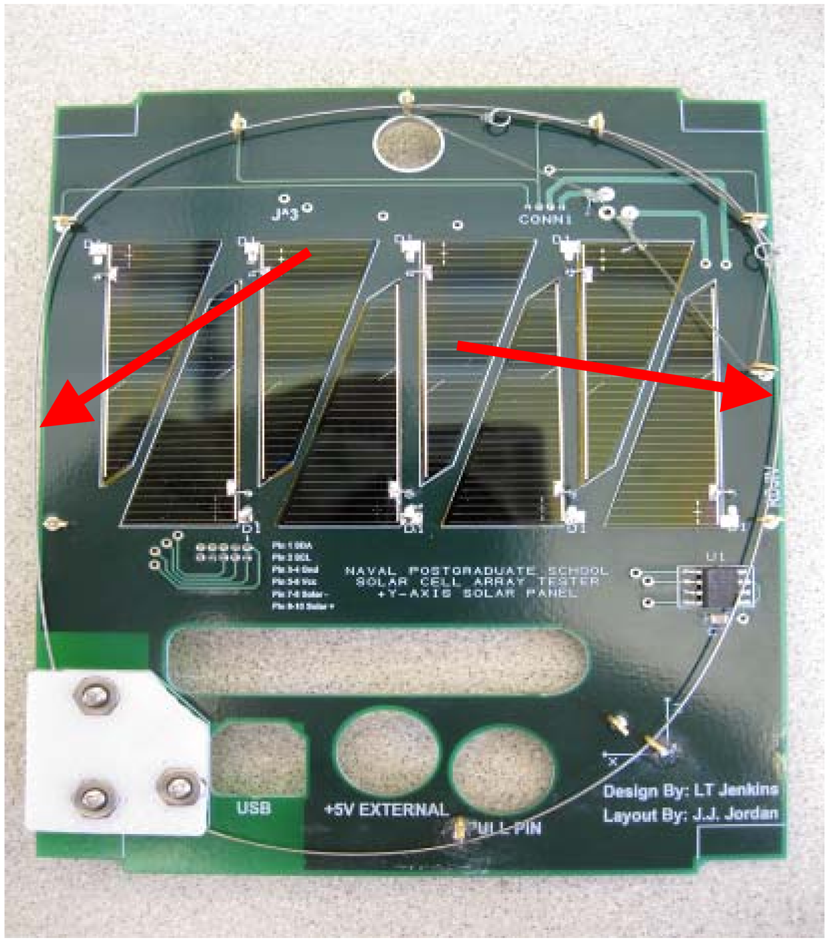

Figure 25. NPS-SCAT +y-axis board showing Beacon antenna violating the CubeSat standard

With more rigorous reviews to ensure stricter compliance to standards, the team may have been able to avoid this problem and have eliminated the need to spend the additional funds. However, development of new systems can always be expected to produce some surprises requiring rework.

1. SCHEDULE

The scheduling process in an educational environment was a challenging endeavor. This is due to the many time requirements on the subsystem managers. These time commitments include class, homework, exams, and the normal pulling and pushing of everyday life. For this program, the workers were not dedicated solely to the project, but had to split their time between the aforementioned commitments and their thesis project.

The schedule then became a task list instead of a true schedule that had to be adhered to. This in and of itself is not necessarily bad. Where this becomes an issue is when a task becomes stalled while it is waiting on another task to complete. This happens when the team members are not on the same schedule and have competing priorities. However, these challenges can be mitigated via a good understanding of the tasks that need to be accomplished and where the intersecting or competing tasks occur. Table 8 shows the tasks remaining to build the SCAT flight units. The tasks are to be accomplished in the listed order. For example, task number 23, integration of the S-Band patch antenna on +z-axis solar panel, should be accomplished prior to conformal coating the panel. Appendix M shows the task list with precedence and a GANT chart.

Number	TASK		Number	TASK	
1	SMS Component Bakeout	Complete	30	+Y Axis Solar Panel component Bakeout	
2	Populate SMS Board	Complete	31	Populate +Y Axis Solar Panel	
3	SMS Funtional Testing	Complete	32	Integrate Beacon Antenna on +Y Axis Solar Panel	
4	SMS Staking		33	Functional Test of Beacon Deployment Mechanism	
5	SMS Conformal Coat		34	Conformal Coat +Y Axis Solar Panel	
6	Determine Bake Time for SMS Post-Conformal Coating		35	Bakeout +Y Axis Solar Panel	
7	SMS Post-Confromal Coating Bakeout		36	Beacon Antenna Functional Test	
8	SMS Pre-Integration Functional Test		37	MHX Acceptance Testing	Complete
9	ESP Component Bakeout		38	FM430 Wire Harness Redsign	
10	Populate ESP		39	FM430 Staking	
11	Functional Test of ESP		40	FM430 MHX integration with MHX	
12	ESP Staking		41	FM430 Component Bakeout	
13	ESP Conformal Coating		42	Reciept of Beacon from Cal Poly	
14	Determine Bakeout Time for ESP Post-Conformal Coating		43	Beacon Board Acceptance Testing	
15	ESP Post Conformal Coating Bakeout		44	Beacon Board Delta Vibe	
16	ESP Pre-Integration Functional Test		45	Beacon Board Functional Test	
17	Machining fo Base Plate	Complete	46	EPS V2 Acceptance Testing	
18	Machining of Cover Plate	Complete	47	EPS V2 Staking	
19	Solar Panel Board Component Bakeout x4		48	Bakeout EPS V2	
20	Solar Panel Build x4		49	Flight Unit CFT	
21	Solar Panel Board Functional Test x4		50	Integrate Flight Unit into Test Pod	
22	Solar Panel Borad Staking x4		51	Vibe Flight Unit To Acceptance Vibe Levels	
23	Patch Antenna Integration with -Z Axis Solar Panel		52	Flight Unit Post Vibe CFT	
24	Funcitonal Test of Patch Antenna		53	Flight Unit TVAC Testing	
25	Solar Panel Board Confromal Coating x4		54	Flight Unit Post TVAC CPT	
26	Determine Bakeout Time Solar Panel Boards Post-Conformal Coat				
27	Solar Panel Board Post Confromal-Coat Bakeout				
28	Solar Panel Boards Pre-Integration Functional Testing x4				
29	Pre-Integration Patch Antenna Functional Test				

Table 8. NPS-SCAT Remaining Tasks

B. BUDGET

The fiscal year 2010 (FY10) budget analysis consists of funds expended to support NPS-SCAT. These funds were expended between January 2010 and September 2010. The FY10 funding received for NPS-SCAT is available until September 2011. As for previous fiscal years, the FY10 analysis included below does not include estimated costs, such as military, faculty labor, or facilities. The next section,

however, includes a full cost accounting to estimate the total cost of the NPS-SCAT program, including estimates for military and faculty labor, and facilities.

1. FY10 Budget Analysis

For FY10, the NPS-SCAT program budget was $69,000.00. The initial allocation of funds can be seen in Table 9. This was an estimate of funding in the areas of travel, equipment, contracts, labor, and indirect cost.

Cost Type	Estimated Funding
Travel	$12,000 (17%)
Equipment	$8,184 (12%)
Contracts	$500 (1%)
Labor	$32,000 (46%)
Indirect Costs	16,346 (24%)

Table 9. 2010 Estimated Budget Allocation

The initial allocation is an estimate only. These allocations can be changed as necessary throughout the period of performance of the work. Figure 26 shows the FY10 actual budget allocation.

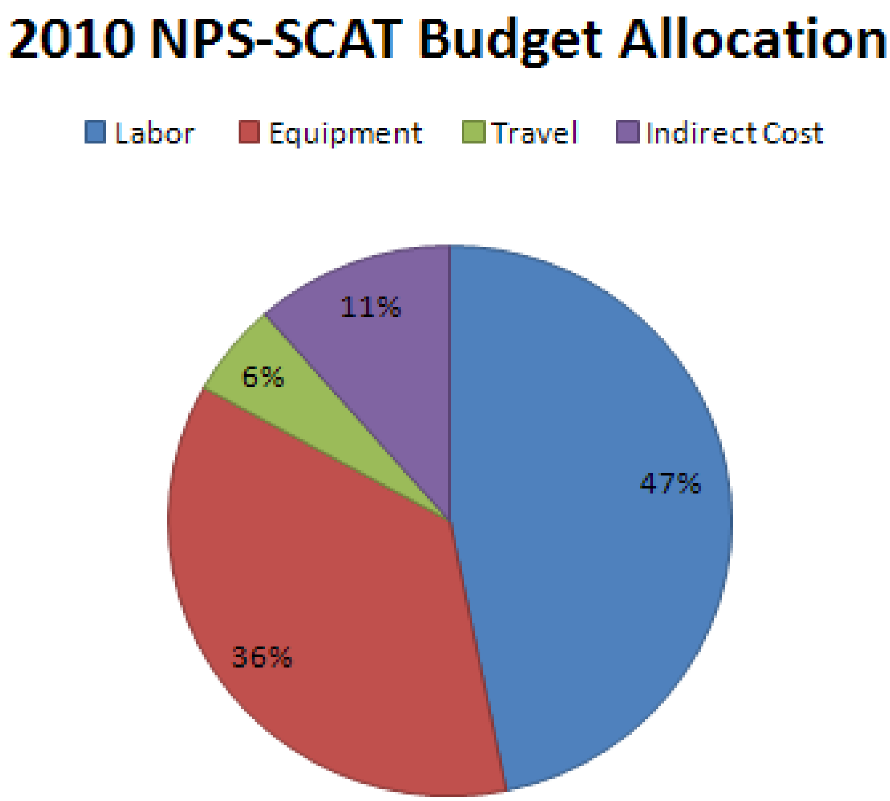

Figure 26. Actual 2010 Budget Allocation

2. Travel

The travel allocation for FY10 was initially set high to accommodate travel to attend the following conferences, CubeSat in San Luis Obispo, Small Satellite in Logan, Utah, and the Department of the Navy (DoN) Space Experiments Review Board (SERB).

Travel to the conferences was not mandatory for the NPS-SCAT team members. For this year, conference travel was minimal. Only six members traveled on the program budget to the April Cubesat Workshop hosted annually by Cal Poly. To save money the team members lodged two to a room, when

possible. Another cost-saving measure was to use Government Owned Vehicles (GOV). The government reimbursement rate for mileage is $0.50 cents per mile for a Privately Owned Vehicle (POV). The total mileage between Monterey and San Luis Obispo is 144 miles one way. Two GOVs were used on this trip, saved approximately $288.00 accounting for reimbursement for two POVs round trip.

Time and workload constraints permitted attendance only at the April CubeSat conference. When presenting NPS-SCAT to the DON SERB was required, a faculty member who was attending the meeting to brief other projects presented NPS-SCAT to the SERB. This saved approximately $2,000.00 of the program budget.

Overall, very little of the allocated travel budget was executed in FY10. This was good for the projects since this money will not expire until September 2011, leaving money for other travel and completion of the flight units, ground station, and operations.

3. Equipment

Major equipment purchases were for the following areas: EPS, structure, solar cell cutting, beacon antenna deployment, and EPS test bed. For this thesis, the author considered a major purchase to be over $1000.00. This number is used since a majority of the purchases were below $1,000.00. These major purchases constituted 44% the total equipment purchases. See Table 10 for list of major purchase

Major FY10 Purchases									
Structure		Beancon Antenn Deploymetn		Solar Cell Cutting		EPS		EPS Test Bed	
1U Coverplate	$1,645.00	`+Y Face		Op Tek	$2,700.00	1U CubeSat EPS	$3,550.00	Banana Binding Post	$213.00
1U Skeletonized CubeSat	$1,825.00	Version 2	$850.00					Binding Post	$419.21
Total	$3,470.00	Version 3	$370.00					Socket Strip	$235.02
		Total	$1,220.00					PCB	$2,306.19
								Total	$3,173.42

Table 10. Break Down of Major Purchases

While all of these items are considered necessary for the program to succeed, not all of them should have been necessary. The Clyde Space EPS Version 2 purchase would not have been necessary, if there was no current leakage in the first version of the EPS. While the work around proposed by Clyde Space could have been implemented, it was determined by the team the newer version of the EPS would provide increased reliability. The beacon antenna deployment mechanism expenditures could have been avoided, if a more rigorous review had been conducted to ensure that the CubeSat standards were met. A more detailed discussion on the beacon deployment mechanism is in the following section. This could have saved potentially $4400.00, a saving of 30%. Equipment purchases of $17,934.00 were 36% of the total expenditure for the year.

Other purchases for this spending period were to ensure there were enough parts to build the flight unit, backup unit testing, and test equipment. For a full list of FY10 purchases, see the Appendix.

4. Contracts

No money was used to fund contracts. Although the FY10 budget spreadsheet in the Appendix has $300.00 for contracts, this is misleading. This reimbursement was for the CubeSat conference fees, considered contracts by the NPS financial system.

5. Indirect Cost

These costs are charged against all sponsored programs to help recover the administration and facilities costs that are not directly billed to a project. It is a fixed rate charged against the account, for FY10 it was 30.97%. It is assessed against all purchases below $5,000.00. To date, the total for indirect costs is $5,648.00.

6. Labor

Labor for the NPS-SCAT program comes primarily from students. The NPS-SCAT students are a mix of military and interns from other schools. The total number of students working the project during FY10 was five military and seven interns. The interns came from a variety of schools including, NPS, Massachusetts Institute of Technology (MIT), Cal Poly, and Hartnell Community College. The students' educational backgrounds varied as well, from those with degrees in Botany and Engineering, to engineering undergraduates and PhD candidates. The military students came from the Navy and Army. All came with various military backgrounds, from submarines, communications, ship drivers, to pilots. This gave the team a large breadth of experience.

While the military and engineering support staff labor is not charged against the program budget, the interns are. For most of the school year, the interns work part time. They shift to full time status during the summer months. The interns are paid an hourly wage and work when they can during the school year and are expected to work full time during the summer.

Intern hours for FY10 totaled $1,419.50, for a total cost of $23,150.00. As part of the intern labor cost, 10% acceleration is added to each paycheck. This is done for all intermittent employees as they do not receive benefits. Labor accounted for 47% of the total NPS-SCAT budget allocation for FY10.

7. NSP-SCAT Complete Cost Estimation

The NPS-SCAT complete cost estimate was done to capture all the costs of the program. To understand the actual program costs, it is necessary to consider costs that are not directly reimbursed. These include estimates of staff, faculty, and military labor, test equipment, facilities, and others. It should also be taken into consideration that during all work the students and even the staff are doing on the project they are also learning. What is the cost of education in terms of positive value? After all that is why the school exists, to educate the students. It is beneficial to take a bottom-up approach and estimate the true cost of NPS-SCAT. The cost estimation will be from project concept in January 2008 through expected launch in FY11.

a. Estimating Labor

Estimating labor for the project, with the exception of intern labor, was difficult. The support staff and faculty are here to support the students. The primary goal for military students at NPS is, of course, education. While getting that education, they must fulfill the thesis requirement for graduation. Those students working on NPS-SCAT do provide valuable labor for the project during their "hands-on" education. To capture the actual dollar value of this labor, the amount of time spent on the project was broken into three time frames, assuming that the total time a student spends on thesis work is equivalent to four months, full-time. Of the 4-month period in which the military students worked on their theses, 1 month will be dedicated to training and getting familiar with the project. During this time, 50% of the hours will be counted as labor toward the project, approximately 10 days. For the next 1.5 months, the student will be completely dedicated to the project, approximately 31 days. The last 1.5 months will be dedicated to writing their thesis. During that time, 20% will be for project documentation, approximately 8 days. Work days will be standard 8-hour days. The number of work days is based on the actual work days in a month and not the total number of days. Military pay charts from 2009 were used as an average to calculate the hourly rate for the military students. This was done to account for the pay raise military members get each year.

All special military pay supplements, flight pay, basic allowance for housing, and basic allowance for sustenance, were used in the calculation of the military

hourly pay rate. The military student hourly rate is based on a year's salary divided by the average number of work days a year (3 year average), with an eight-hour work day. See the Appendix for a complete breakdown of military labor.

The staff and faculty labor was calculated based on the number of hours a week they dedicated directly to NPS-SCAT. The hours worked each week were estimated for each year. Each year, as the project moved from concept to prototype to EDU, the number of hours each week increased, as the work load increased. There were four staff and faculty positions considered: lab manager and electrical engineer, astronautical engineer, software engineer, and principle investigator. The hourly rates were provided by the principle investigator. See the Appendix for a complete breakdown of faculty labor.

Estimated Labor Cost	
Military Student	$280,300.00
Faculty	$233,600.00
Intern	$60,000.00
Total	$573,900.00

Table 11. Estimated Labor Costs

b. Cost of Thermal Vacuum and Vibration Testing

The NPS SSAG has in-house Thermal Vacuum (TVAC) and vibration testing capabilities that were used by the

NPS-SCAT project. To capture the value of conducting the testing in-house, estimates were provided by Quanta Laboratories and NASA Ames Research Center.

Quanta estimated it would take approximately 12 hours to complete a vibration qualification on a 1U CubeSat. To qualify NPS-SCAT, both the EDU and flight unit would have to be qualified. The hourly rate of $210.00 covers the cost of labor, but there are additional fees for instrumentation and reports. The total cost is estimated to be $6040.00 to complete vibration testing on NPS-SCAT.

TVAC testing was estimated by NASA Ames to take four days of twenty-four hour testing (From a conversation with NASA Ames Engineer Orlando Diaz, on September 19, 2010). A total of three engineers would be required to complete the testing, one on call and two on rotating shifts operating the chamber. It is assumed the on call engineer would accumulate 10 hours and there would always be at least one engineer operating the TVAC chamber. The hourly rate charged by NASA Ames is $128.00 to use the TVAC chamber, and this rate does not include labor. The hourly rate for the engineers is estimated to be about $82. Instrumentation and report fees are assumed to be about $300 and $200 respectively. Again, both the EDU and flight unit would have to undergo TVAC testing. The total cost for both would be estimated at $49k.

The total NPS-SCAT testing budget estimate, if testing was conducted outside NPS, would be $55k. This would be a significant cost considering the FY10 budget was only $69k.

Now that the estimated cost of contracting out testing is known, what is the cost of having in-house testing equipment? It begins with the cost of the vibration test equipment, including all related equipment needed to conduct testing, which is approximately $119k. The TVAC equipment cost, again assuming all related equipment required to conduct testing was approximately $12k. That is approximately $131k for both capabilities. However, this is not the cost that should be allocated to the NPS-SCAT program. The lifetime cost for the capability must be accounted for. To do this, the TVAC and vibration equipment cost was amortized over 15 years—15 years was assumed to be the operating life of the equipment. A 5% annual cost was assumed for maintenance of the equipment. The total lifetime cost for the TVAC would be $17k and the vibration equipment would be $162k. The total lifetime cost for both would then be ~$180k. Currently, there are three projects that are using these facilities. Assuming there are always three programs splitting the cost evenly for each FY, that would leave SCAT responsible for $4k a year.

It would seem that it is much less expensive to use in-house facilities, than to use outside contractors to do qualification testing. This is without considering the value of education. It only costs $4k or so to have students getting hands on experience conducting vibration and TVAC testing, in the Case of the NPS-SCAT project. Key Performance Parameter (KPP) 001 of the NPS-SCAT project states, ***The satellite development program shall provide NPS students with an education in the satellite design process, integration, testing, and full life cycle of a space flight system.*** Therefore, like paying for subsystems to meet the

other KPPs, paying to educate students is also worthwhile. It should be understood that the students researched and built their own testing profiles for each test and once trained, conducted the training with little support from faculty. The experience gained from this can be taken with them when they leave and applied either to specific space projects, or to general understanding of integration and test. In the case of the military students, many of them may actually go on to program management jobs in the space community.

For the purposes of this cost estimate, the value of the TVAC and vibration test equipment cost estimate used will be the $4k.

c. Lab Equipment

Lab equipment cost had to be estimated as well. Prior to the start of the NPS-SCAT project, the CubeSat Development area in the Small Satellite Lab only had limited facilities for CubeSat work. Once NPS-SCAT started, computers, desks, multi-meters, and other various pieces of lab equipment were purchased using various funds other than the NPS-SCAT project funds. These costs are included as part of estimated cost of NPS-SCAT. The total cost for this equipment was $87k. This should also be amortized over 10 years at 5 %, coming to about $110k, splitting this between the three projects. The total cost for SCAT is about $4k yearly. For a complete list of lab equipment and prices, see the Appendix.

d. Materials

The material cost estimate should account for future purchases, as well as past. Current inventory only has one Clyde Space Version 2 EPS, which will be used on the flight unit. This includes a battery daughter board. Therefore, a Version 2 EPS should be purchased for the backup flight unit, as well as another battery daughter board. This will put an extra battery in the inventory. The cost for these items is approximately $4500. The S-Band ground station antenna will require another $5k to complete the refurbishment. Another $1k will be added to account for any unknown costs—bringing the total assumed future cost to about $11k. This is the estimated amount needed for the project to accomplish one satellite in orbit and one back up satellite waiting for launch. The total estimated materials cost for NPS-SCAT, flight and backup, is about $107k. For a complete breakdown of material cost, see the Appendix.

e. Travel

Future travel costs for FY11 were estimated by averaging the travel cost from FY08 and FY09. FY10 was not used for the estimate, since it was an atypical year for travel. The estimated cost for FY11 is $6k. Total travel cost estimate for NPS-SCAT is $21k.

f. Total Cost Estimate

The NPS-SCAT total cost estimate is outlined in Table 12.

Total NPS-SCAT Cost Estimate ($k)	
Labor	$574
Materials	$107
Travel	$21
Vibration and TVAC	$12
Lab Equipment	$9
Total Estimate	$724

Table 12. NSP-SCAT Total Estimated Cost (in $k)

This may seem high for a 1U CubeSat, but the estimate assumes you are starting from the ground up and is focused primarily on education as opposed to production. When looked at from that perspective, it is not unreasonable.

g. Comparison

In comparison, an estimate for building a 1U CubeSat came in at $52k on the website SatMagazine [34]. This price included the cost of launch but did not include labor, testing, or any type of equipment. If the launch cost is taken out, the price to construct that satellite would be approximately $30k. To build NPS-SCAT, the cost would be the material cost of $102k. This price includes two satellites, a flight unit and back up. Therefore, the price to build just one NPS-SCAT satellite would be half of that or $51k. 1U Cubesats typically range in price (materials only) from $30k to $40k [35]. NPS-SCAT is still a higher price than the estimate from SatMagazine or the average cost, but it is also a more complex satellite, with

a more expensive payload. Looking at construction only, even though it is somewhat higher, it is still on par with the price of the average 1U CubeSat.

IV. ORBITOLOGY

A. NPS-SCAT ORBITAL PARAMETERS

NPS-SCAT will be launched into a low earth circular orbit. The exact orbital parameters are not known at this time. The orbit altitude could be as low as 350 kilometers (km) to a high of 650 km. The orbit inclination will be approximately 45 degrees.

1. Circular Orbits

Circular orbits are characterized by having a constant radius. The radius of a circular orbit is a function of angular momentum and the earth's gravitational parameter mu (μ). Having a constant radius also means that the velocity of a satellite in a circular orbit will remain constant [36], [37].

2. Analysis of Separation from Companion Payload

NPS-SCAT is expected to share the P-POD with the Rapid Prototyped Micro-Electro-Mechanical System Propulsion and Radiation Test Cubeflow Satellite (RAMPART) [38]. RAMPART is a rapid prototyped or printed satellite, meaning that most of the satellite has been constructed with a 3-D printer. It will be a technology demonstration and qualification mission for several subsystems [38]. Of interest to the SCAT team is the printed warm gas propulsion system, to include tanks and nozzles [38]. SCAT's sun sensor could be affected, if SCAT is near RAMPART when it begins testing its propulsion system. According to the CubeSat standard, all

CubeSats must wait 30 minutes after they are deployed to start up. In addition, RAMPART will not start testing its propulsion system for another five days after deployment. A preliminary, quantitative analysis, using STK, has been conducted to estimate the separation distance between the two satellites after five days.

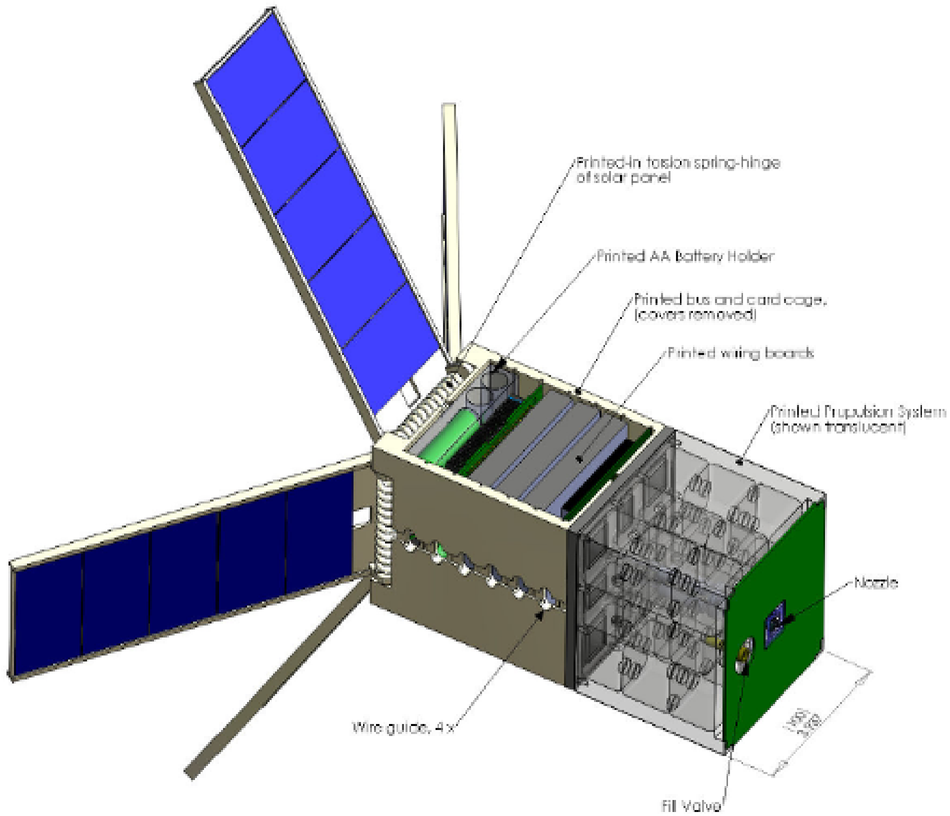

Figure 27. RAMPART With Solar Panels Deployed (From [38])

a. ***Modeling SCAT and RAMPART Separation with Satellite Tool Kit (STK)***

It is not known what orientation to the orbital plane the CubeSats will be when ejected from the CubeSat launchers. Therefore, this analysis was conducted for three separate cases. A small spring will separate the satellites at approximately 5 millimeters/second (mm/s) relative

velocity [39]. The type of spring, a "foot spring," is set by the CubeSat standard. All cases were analyzed with an orbit altitude of 450 km and an inclination of 45 degrees. Figure 28 shows the orientation of the X, Y, and Z axes for the analysis. The axes were defined in this orientation for use with STK.

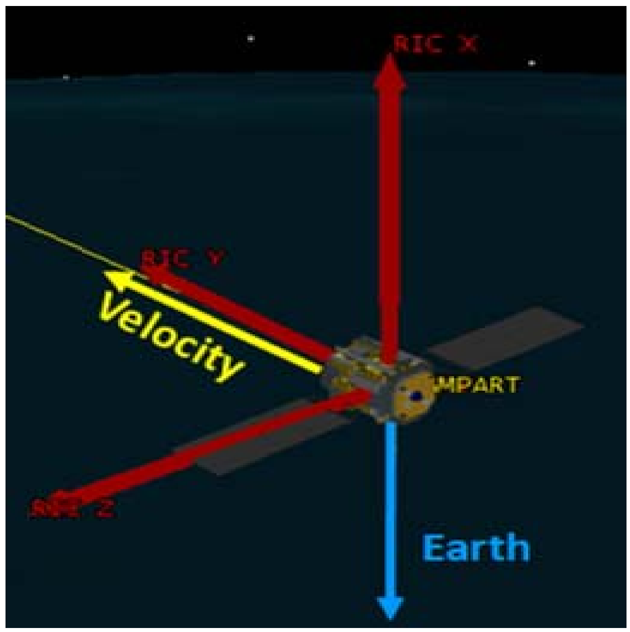

Figure 28. X,Y,Z Axes

b. Case 1

This case was the simplest case. It did not take into account atmospheric drag or any perturbations and the satellite masses were equal. This case analyzed only the effects of the force of the spring separating the satellites. Four different Scenarios will be analyzed.

- Scenario 1 – 5 mm/s added to SCAT in the radial direction or x direction
- Scenario 2 – 5 mm/s added to SCAT perpendicular to the direction of motion, or z direction

- Scenario 3 – 5 mm/s added to SCAT in the direction of the motion or y direction
- Scenario 4 – A total of 5 mm/s added to SCAT in (x,y,z)

Scenarios 1-3 illustrate the cases where the velocity added by the foot spring is in a single axis for each case. The more likely situation will be something like Scenario 4 with the velocity being added, and having a component in all axes.

Scenario 1 adds a velocity in the radial or x direction. This places SCAT in a slightly elliptical orbit, but with the same energy and, therefore, the same period. As SCAT slows on its way to apogee, it separates from RAMPART. After SCAT passes through apogee, its velocity increases as it moves to perigee, intersecting RAMPART at perigee. Figure 29 shows a graph of the in-track separation distance.

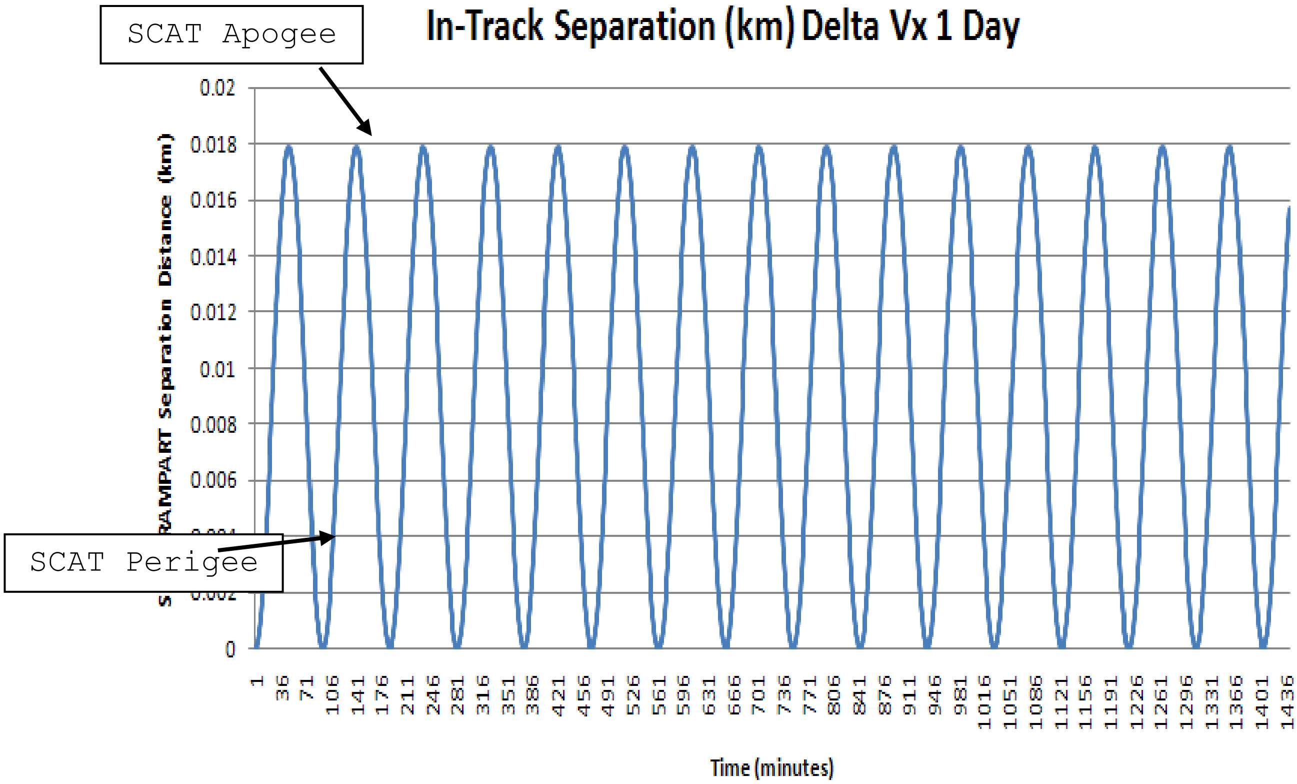

Figure 29. SCAT/RAMPART CASE 1 Separation Distance, 1 Day, Delta Vx=5 mm/s

Scenario 2 also adds velocity perpendicular to the direction of motion and so the period does not change. In this case, there is no change in the distance between the two CubeSats from Scenario 1. The velocity of a circular orbit is only dependent on the radius the orbit. To change the velocity of SCAT, and therefore, the distance between SCAT and RAMPART, the semi-major axis of SCAT's orbit must change. The change in the perpendicular component of velocity does not change the radius of the orbit, so with no other forces acting on the satellites, SCAT and RAMPART do not separate.

Scenario 3 adds velocity in direction of motion. This increases the energy of the orbit and puts SCAT in a slightly elliptical orbit, but unlike Scenario 1, SCAT will not meet RAMPART at perigee. SCAT reaches perigee at a different time in its orbit, since initially it passes RAMPART due to the increase in velocity. As SCATs radius increases though, its velocity decreases, and RAMPART over takes it, being in a lower orbit and, therefore, faster on average. The distance between the two satellites will steadily increase. In one day, the satellite will separate by approximately 1.3 km. Figure 20 shows the in-track separation distance over 1 day.

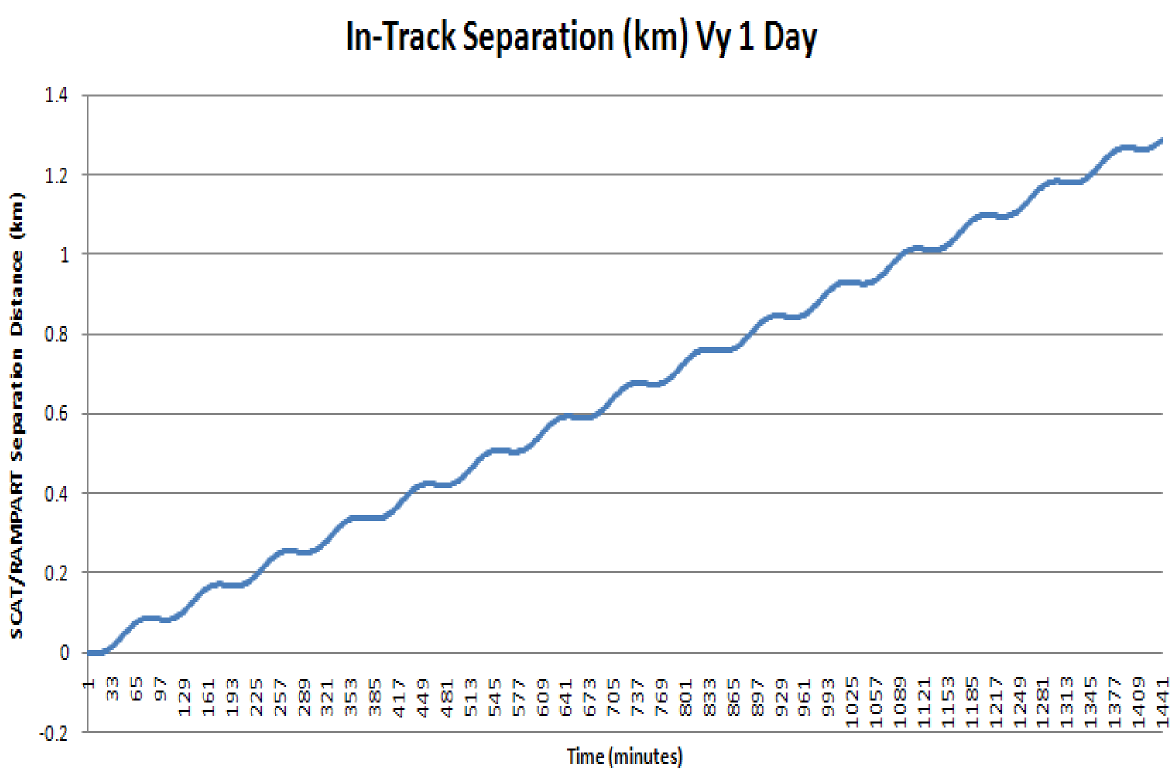

Figure 30. SCAT/RAMPART CASE 1 Separation Distance, 1 Day, Delta Vy= 5 mm/s

Scenario 4 adds a total magnitude of 5 mm/s with an equal component of the velocity added in each axis. All component velocities added were equal, approximately 2.88 mm/s. This results in a 1 day separation distance of roughly 1.06 km. This is slightly less than Scenario 3, due to the fact that the perpendicular component does not add to the change in the radius. Because of this, the velocity will not decrease as much, resulting in a lower separation distance. Figure 31 shows the in-track separation distance over 1 day for this case. Again, the waves in the graph can be seen in Scenario 3.

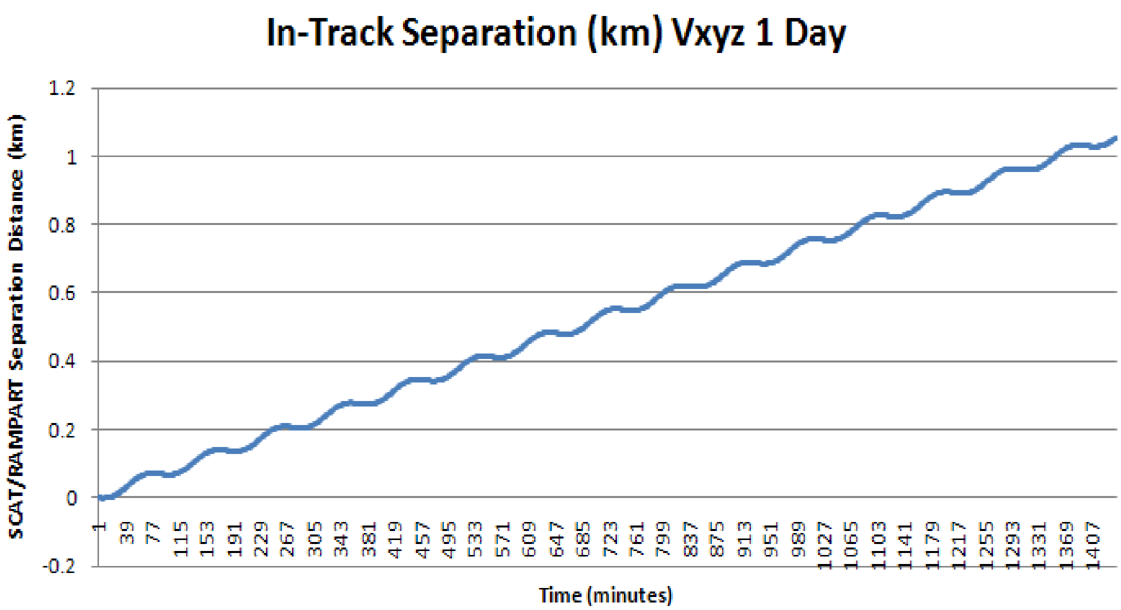

Figure 31. SCAT/RAMPART Case 1 Separation Distance, 1 Day, Delta Vxyz=5 mm/s

c. *Case 2*

This case only analyzed the effects of atmospheric drag and without a change in velocity. The Harris-Priester atmospheric model was used with the High Precision Orbit

Propagator (HPOP). The value used for SCAT's cross-sectional area was 0.013 meter^2 (m^2), with a mass of 1 kg [17]. The cross sectional area for RAMPART was taken to be 0.0195 m^2, with a mass of 2 kg. The values corresponded to an area to mass ratio of 0.013 m^2/kg and 0.00975 m^2/kg. It should be noted that the cross sectional area use was calculated for RAMPARTs stowed configuration. The actual cross sectional area will be larger with the solar panels deployed, changing RAMPARTS area to mass ratio. With these parameters, the separation distance after 1 day was approximately 2.2 km. This is about 70% more than that of Case 1; Scenario 3 and 4, showing that with such a small change in velocity, drag is the dominant force in separation. With a larger area to mass ration, RAMPARTs would overtake SCAT, as its altitude decrease and its velocity increases. Figure 32 shows the in track separation distance that is seen in the other graphs.

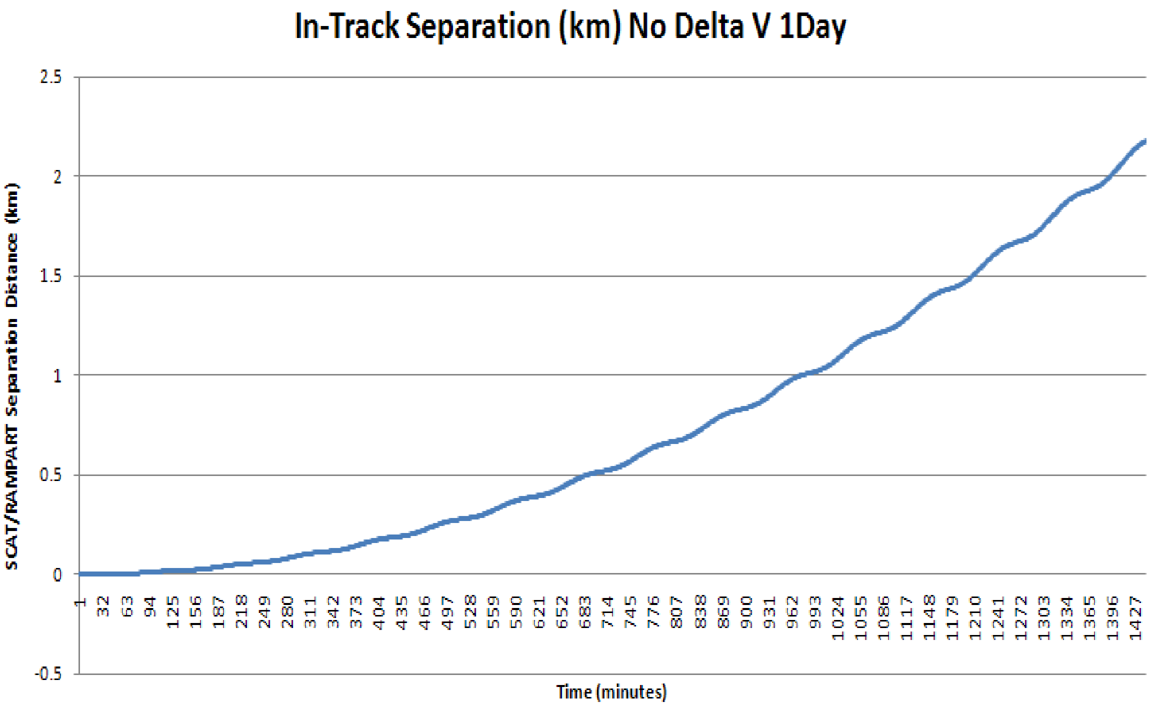

Figure 32. SCAT/RAMPART Case 2 Separation Distance 1 Day Atmospheric Drag with no Delta V

d. Case 3

This case combined Case 2 and Case 1, Scenario 4. This case is set with the same parameters as Case 2, with the added change in velocity of Scenario 4. The change in velocity causes the radius of SCATs orbit to increase, corresponding to a decrease in velocity. As seen in Figure 33, the initial values are negative. The negative values are due the reference frame used for the plot, the direction of motion is positive, therefore as SCAT initially falls behind RAMPART, the distance is negative. However, as seen in the previous case, atmospheric drag dominates, and over time, SCAT's orbital altitude begins to decrease, increasing its velocity. After roughly seven orbits, SCAT's velocity has increased enough to catch and overtake RAMPART. In the

case of RAMPART's solar panels being deployed, SCAT and RAMPART would switch, with RAMPART initially falling behind SCAT and then overtaking sometime later. The separation distance over 1 day for this case is approximately 1.1 km. This is less than the previous two cases because SCAT has to overcome the initial distance it fell behind RAMPART. This also shows that atmospheric drag is the dominant factor in separation.

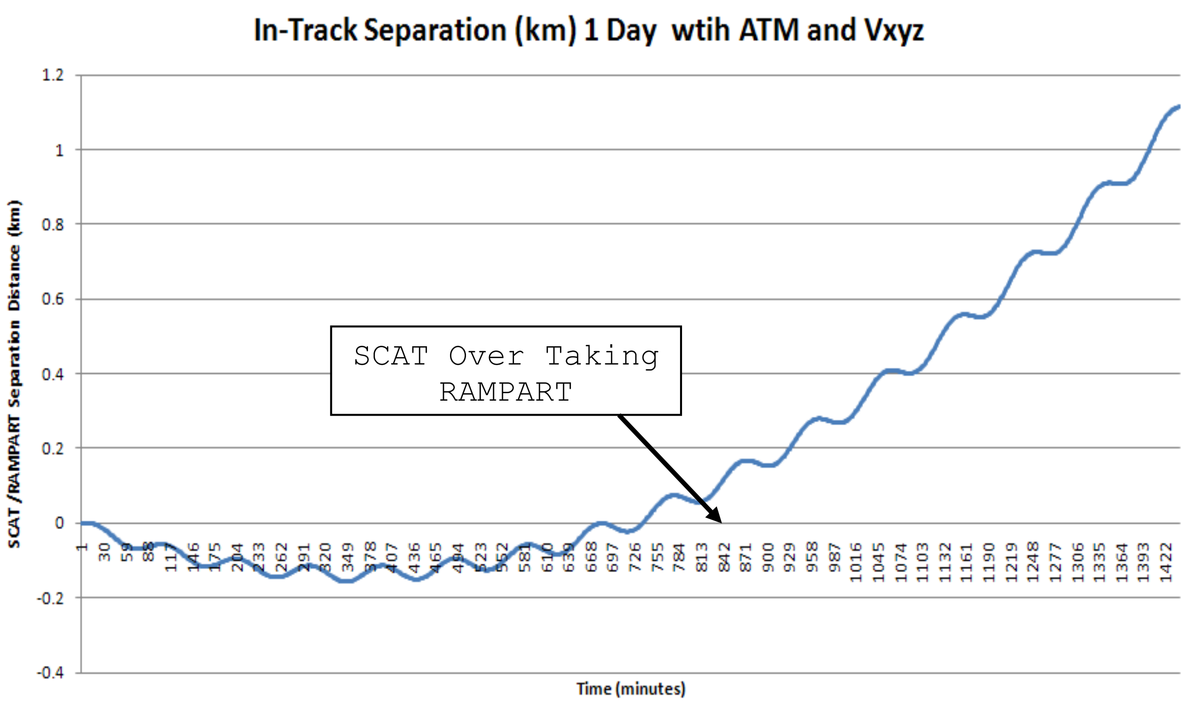

Figure 33. SCAT/RAMPART Separation Distance 1 Day Atmospheric Drag and Delta Vxyz=5 mm/s

e. Conclusions

It is clear from the STK models that the dominant force acting to separate SCAT and RAMPART is atmospheric drag, as long as there is a real difference in their ballistic drag coefficients. The amount of force imparted by the CubeSat foot spring is small relative to the drag

force. With RAMPART solar panels deployed, therefore, a larger area to mass ratio, the trend will be the same with RAMPART moving away from SCAT with a higher velocity. Over a 5-day period SCAT and RAMPART will be approximately 48 km apart using Case 3 parameters. Over the same amount of time, using Case 1 parameters, the two satellites will be separated by approximately 5 km. When RAMPART starts testing, its propulsion system SCAT will be at a safe distance and should not be affected.

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V. CONCLUSION

A. FUTURE WORK FOR NPS-SCAT

1. Build Flight and Backup Units

The flight and backup units' construction should be the priority task to be completed. To date, the preliminary work has begun on the construction of the SMS for both units. All subsystem items will have to undergo acceptance testing, integration, and qualification testing. This must be completed sometime between February and May 2011, the date for delivery to the flight integrator.

One issue that is currently not resolved is the Cal Poly beacon board. As of this writing, only one working board has been delivered. This board has been tested with the antenna and works satisfactorily. The team has made revisions to the beacon board and sent the changes to Cal Poly, and they integrated the changes in to revision 2 of the beacon board. Revision 2 is currently waiting to be ordered.

2. Testing

The EDU has completed vibration testing to NASA GEVS +6dB. The EDU has also completed a series of post vibration functional tests. All tests were completed satisfactorily. A single cycle TVAC test was also conducted. The cold soak was aborted to maintain the battery at a safe temperature, above -10 degrees Celsius, due to a possible problem with the battery heaters. The EPS subsystem manager is currently

corresponding with the manufacture on this issue. Therefore, it is recommended that during acceptance testing of Version 2 of the EPS, that a battery heater test be incorporated.

During the testing of the EDU, the operational beacon board was not integrated. The beacon is the only component that has not been tested to qualification levels. It has to be determined how vibration qualification testing on the beacon should be conducted. It is recommended that the qualification testing be conducted on the Version 2 of the beacon, if possible.

As part of pre-flight testing, the experimental solar cells will need to be characterized. This will provide a baseline to compare with the data received from the satellite.

3. MHX 2400 Ground Station System

The ground station for the MHX 2400 is currently not operational. The dish on top of Spanagel Hall, which will be the antenna, is currently being refurbished, but is not yet complete. Detailed ground station refurbishment requirements are in [23].

4. Launch and Operations

The ground concept of operations needs significant work. Some work has been completed in the past, but more work is required. Questions that need to be considered are how the data will be collected from amateur radio operators that download beacon data. The data will need to be

organized and analyzed, and results recorded. Students working on this or the ground station should have their amateur radio license.

B. MILITARY APPLICATIONS FOR SMALL SATELLITES

Traditionally, the military uses space for intelligence gathering and communications. Under the umbrella of intelligence, there is imaging, surveillance, and reconnaissance. These applications have traditionally been carried out by large and expensive satellites. As the military looks forward to the future space force, it will probably see smaller budgets that may not accommodate as many of these behemoths of space as in the past. The Transformational Communication Program was canceled for being over budget and behind schedule, and the recent budget proposal for NASA canceled the organic heavy lift capability of the U.S. government, and shifted it toward commercial launch providers.

Imagery capability by small satellites is not necessarily expected to achieve the high spatial resolution of the larger satellites, suffering from aperture size limitations as they are, although the ability to image has been demonstrated in small satellites, such as DRL-TUBSAT. While this is traditionally considered a micro-satellite at 45 kg, it achieved a resolution of 6 meters from an altitude of 726 km. Even more impressive, was the Micro Electrical-Mechanical Propulsion Systems (MEPSI), which launched on the STS-116 space shuttle mission [1]. In this experiment, nano-satellites were tethered by a 60-foot wire. This

experiment demonstrated the ability to maneuver with reaction wheels and thrusters to take images of the space shuttle.

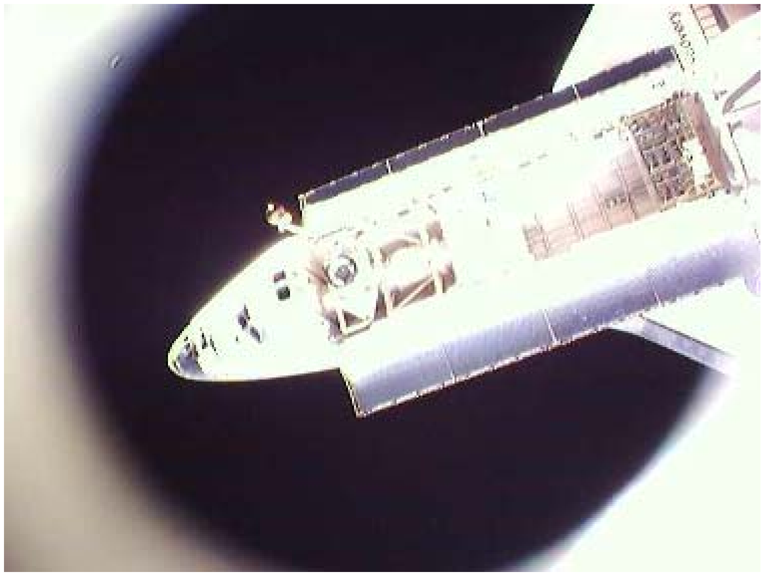


Figure 34. The Space Shuttle Imaged by one of the MEPSI Nanosatellite (From [1])

While these are not high resolution images, they do demonstrate the capability of small satellites to image both the earth and objects in space.

A future 6U CubeSat being developed at NPS, TINYSCOPE, will provide tactical imagery, 3-4 m resolution at 30 minutes revisit time, to the war fighter. The 6U CubeSat will be two 3U CubeSat structures side by side. The TINYSCOPE EDU is currently under construction [40].

Small satellites also have a role in defensive and offensive space operations. AeroAstro’s Escort program evaluated applications to monitor space, perform stealth inspection, attack, and defend larger satellites using microsatellites [41]. The program would turn microsatellites

into possible anti-satellite weapons. The Air Force was a major sponsor of this program. Another program that has military applications is the Demonstration of Autonomous Rendezvous Technology (DART) program launched in April 2006 [41]. The spacecraft rendezvous with a retired communication satellite and performed a series of close proximity maneuvers. The DART spacecraft also made contact with the communications satellite and boosted it to a higher orbit. These capabilities have both peacetime and direct military applications. These technology demonstrators have proven they can have a significant role in the future of Space Situational Awareness.

Small satellite communications applications have also been demonstrated. Another TUBSAT–A is a store and forward communications satellite that was launched in 1991. Its payload was a VHF communications payload operating at 143.075 MHz, and radiating at 2W. While this is not significant in terms of transmit power and bandwidth, it demonstrates capability [1].

While not all the spacecraft and concepts mentioned in this section are CubeSats, it shows that miniaturization of spacecraft can be relevant to military operations. Although there will not be a CubeSat revolution in military space systems anytime soon, as CubeSat technology matures, it is more likely than not that there will be missions for CubeSats in the future of military operations.

C. SUMMARY

From the development of the Key Performance Parameters to the completion of qualification testing, the lessons

learned provide a base for the next generation of NPS CubeSats. Managing SCAT has presented many challenges, chief among them implementing a policy of: “trust but verify.” Acceptance testing and documentation are actions that must be accomplished. Failure to do so will cost time and money. The EPS is an example of this. There is a reason it takes a team to build a satellite. Every team member is an extra set of eyes to review another team member’s work. Understanding the design review process is important in the program management process. Schedules in the educational environment are better used as task lists, this is still very important even though they don’t necessarily tell you when you will get there, they will tell you how. All throughout the program, from initial concept to on-orbit operations, risk must be accepted. There is no constant level of risk, it is always in flux. Trying to mitigate all risk out of the program would become costly. The program manager needs to do what he/she can to mitigate risk by applying lessons learned, testing, and conducting design reviews. In the end some risk will have to be accepted.

The use of NPS-SCAT as educational tool is invaluable. The NPS-SCAT project alone has produced 12 Master’s Theses providing for the education of many military officers. It has also provided the opportunity for hands on experience in building and testing of CubeSats. The NPS-SCAT project has also afforded these same opportunities to civilian college students. This demonstrates that CubeSats provide a valuable component in the education of space professionals.

APPENDIX. BUDGET SPREADSHEETS, CHARTS, AND DIAGRAMS

A. COMPLETE LIST OF COMMAND ACTIONS

1. h (0x68) – check MHX functionality
Sends back a simple string over the MHX radio to verify that the MHX radio is working.

2. b (0x62) – check beacon functionality
Sends back a simple string over the beacon radio to verify that the beacon radio is working.

3. a (0x61) – deploy beacon antenna
Commands the satellite to attempt to deploy the beacon antenna.

4. ? (0x??) – get beacon antenna deployment state
Reports via MHX whether the deployment sensor determines the antenna is deployed or not.

5. e (0x65) – get EPS state
Gathers all EPS state information and reports the entirety via the MHX radio.

6. i (0x69) – gather IV curve
Conducts the I-V curve data collection routine on all four experimental solar cells and reports the results via the MHX radio.

7. d (0x64) – get real time clock date
Gets the date from the Real Time Clock and reports it via the MHX radio.

8. s (0x73) – get sun sensor temperature and vector
Gathers all the data from the sun sensor and reports the results via the MHX radio.

9. t (0x74) – get temperatures
Gathers temperature information from all 15 temperature sensors and reports the results via the MHX radio.

10. ? (0x??) – turn on beacon radio

Turns on the beacon radio. Obviously this command must be sent via the MHX if the beacon is initially turned off.

11. ? (0x??) – turn off beacon radio

Turns off the beacon radio. To maintain communication, ensure that the MHX radio is turned on and working.

12. ? (0x??) – turn on MHX radio

Turns on the MHX radio. Obviously this command must be sent via the beacon if the MHX is initially turned off.

13. ? (0x??) – turn off MHX radio

Turns off the MHX radio. To maintain communication, ensure that the beacon radio is turned on and working.

14. m (0x6D) – turn on SMS board

Turns on the SMS board +5V.

15. n (0x6E) – turn off SMS board

Turns off the SMS board +5V.

B. LIST OF FY10 PURCHASES

Document #	Vendor	Description	EE	Actual Cost
0MDR9Q11	MixW	Software License for NPS-SCAT Ground Station	T	$50.00
0MDR9Q17	McMaster-Carr	MIL Spec Pan Head Philips Machine Screw,2-56 threa	T	$209.02
0MDR9Q18	Tower Hobbies	K&S Music Wire .015" Dia(4),LXYMK8,Round brass	T	$28.47
0MDR9Q19	Pasternack Enterprises	3" extension plug to plug 4 each,6" extension plug	T	$256.80
0MDR9Q20	Digi-key Corporation	IC Buff/DVR Tri-St DL 8VSSOP, TI 10 each	T	$77.20
0MDR9Q21	Advanced Circuits	Printed circuit board,p/n +Y Axis_rev 2 5 each	T	$894.81
0MDR9Q22	McMaster-Carr	Metric 316 SS Pan head phillips machine screw,M2.5	T	$68.79
0MDR9Q23	Tower Hobbies	K&S Music Wire .015x36" (25),K&S, LXWU94,Brass	T	$20.67
0MDR9Q24	Digi-Key Corporation	IC Buff/DVR tri-ST DL 8VSSOP, TI	T	$54.02
0MDR9Q25	Bellin Dynamic	Lab Pro 10 snap-apart kit,Bellin Dynamic Sys, K910	T	$397.50
0MDR9Q26	Pasternack Enterprises	Extension MCX Plug to MCX Plug R-Angle 50 ohm 3 ea	T	$133.15
0RQR9Q01	FedEx	Ship box to Greenville,SC and return frm SC to NPS	L	$4.62
0RQR9Q02	Techni-Tool, Inc.	Techni-Stat Mini Vacuum Handling Tool,with 4 probe	T	$45.41
0RQR9Q03	Newark	Standard D-Subminiature Connector - 2	T	$122.96
0RQR9Q04	Samtec Silicon Valley	SAMTEC elevated double row socket strip,0.100"(2.5	T	$62.60
0RQR9Q05	Pasternack Enterprises	UMCX Plug to UMCX Plug,1/13mm COAX,12" - 5	T	$45.86
0RQR9Q06	Digi-Key Corporation	CONN RECEPT 3POS 3MM Single Row-10 each	T	$180.74
0RQR9Q07	amazon.com	Brother 3/8 Inch x 26/2 feet black on white tape	T	$61.45
0RQR9Q08	Jameco Electronics	Wire Jumper Reinforced,8"L,W/R/Y/B/BK,10PCS	T	$69.15
0RQR9Q09	McMaster-Carr	3/8"-16 threaded rod,6'length:316 SS;P/N:94400A160	T	$35.06
0RQR9Q10	B&H Photo Video	Canon PowerShot A3000 IS Digital Camera w/Basic	T	$152.50
Subtotal for:				**$2,970.78**
0MDR9Q27	Advanced Circuits	Printed circuit board,Part number +Y Axis_rev3	T	$368.23
0MDR9Q28	Mouser Electronics	Banana binding post conn yellow gold,pomona electr	T	$213.00
0MDR9Q28x	Digi-Key Corporation	Binding post gold plated red,pomona electronics	T	$419.21
0MDR9Q29	Advanced Circuits	Printed circuit board,CSK_TB1 Rev 1	T	$2,306.19
0MDR9Q31	Samtec Silicon Valley	SAMTEC elevated double row socket strip,0.100"	T	$235.02
0MDR9Q32	McMaster-Carr	Rubber bumper w/washer 1/2" base,1/4"H,Metric pan	T	$9.90
Subtotal for:				**$3,551.55**
Total				$6,522.33

Pumking Stand Offs	Pumpkin	Mid-Plane Stand Off	$625.00
Toos	Techi-Tool	Tools	$157.00
CoverPlate	Pumpkin	Cover Plate Assembly	$1,645.00
Si Solar Cells		Si Solar Cells	$65.00
Experimental Solar Panel	Advanced CKTS	ESP	$413.00
EPS	Clyde Space	ESP Version 2	$3,550.00
EXP Solar Cell Cutting	OP Tek System	Solar Cell Cutting	$2,725.00
Antenna Wire	Tower Hobies	Piano Wire	$26.00
CubeSat Structure	Pumpkin	1U CubeSat Structure	$1,825.00
PCB (X,Y)	Advanced CKTS	X and Y Boards	$381.00
Total			$11,412.00

Total for FY 2010	$17,934.33
Total from 2008 From Bein	$25,551.47
Total from 2009 From Molone	$53,190.00
Total 2011 Estimate	$10,500.00
Total Equipment	$107,175.80

C. FY10 BUDGET SPREADSHEET

NPSSCAT Budget FY10 R789Q

Item	Requisition Number	Company	Oct ($)	Nov ($)	Dec ($)	Jan ($)	Feb ($)	Mar ($)	Apr ($)	May ($)	June ($)	July ($)	August ($)	Sept ($)	Oct ($)	Yearly Total ($)	Target ($) (Beginning of year)
Labor			0.00	0.00	0.00	1259.87	1527.88	1088.78	1447.36	567.72	2228.63	926.29	0.00	0.00	0.00	9046.53	32000.00
Intern 1			0.00	0.00	0.00	559.94	941.02	699.93	591.05	155.54	1119.89	279.97	0.00	0.00	0.00	4347.34	
Intern 2			0.00	0.00	0.00	699.93	412.18	388.85	777.70	412.18	287.75	0.00	0.00	0.00	0.00	2978.59	
Intern 3			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	622.16	0.00	0.00	0.00	622.16	
Intern 4			0.00	0.00	0.00	0.00	174.68	0.00	78.61	0.00	821.00	646.32	0.00	0.00	0.00	1720.60	
Intern 5			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Travel			0.00	0.00	0.00	0.00	0.00	0.00	2424.50	0.00	0.00	0.00	0.00	0.00	0.00	2424.50	12000.00
Equipment, Hardware, Software, Supplies			0.00	0.00	0.00	0.00	0.00	0.00	6467.91	0.00	0.00	0.00	0.00	0.00	0.00	6467.91	8184.00
a) E&S less than $5k			0.00	0.00	0.00	0.00	0.00	0.00	6467.91	0.00	0.00	0.00	0.00	0.00	0.00	6467.91	
2010/04/09Shipping for Solar Cells	0RQR9Q01	FeDEx							4.62								
2010/04/09Vacuum Handling Tool	0RQR9Q02	Techni-Tool							45.41								
Standard D-Subminiature Connector - 2	0RQR9Q03	Newark							122.96								
Samtec Elevated Double row Sockets Strip	0RQR9Q04	Samtec							62.20								
UMCX Plug to UMCX Plug 1/13mm Coax 12' - 5	0RQR9Q05	Pasternack							45.86								
Conn Recept 3pos 3mm Single Row-10	0QRR9Q06	Digi Key Corp							180.74								
3/8' threaded rod 6' length 316 SS,P/N 94400A160	0QRR9Q09	McMaster Carr							35.06								
Brother 3/8in 26/2 feet black on with tape	0RQR9Q07	Amazon.com							61.45								
Wire Jumper Reinforced, 8'L, W/R/Y/B/BK 10PCS 24AWG	0RQR9Q08	Jameco Elec							69.15								
Cannon PowerShot A3000 IS Digital Camera	0RQR9Q10	B&H Photo							152.50								
Software Lic NPS-SCAT Ground Station	0MDR9Q11	MixW							50.00								
MIL Spec Pand Head Philips Machne Screw, 2-56	0MDR9Q17	McMaster Carr							209.02								
K&S Music Wire .015" Dia(4), LXYMK8 Rround Brass (BCN)	0MDR9Q18	Tower Hobbies							28.47								
3" extension plug to plug 4 each, 6" extention plug	0MDR9Q19	Pasternack							256.80								
IC Buffer /DVR Tri-St DL 8VSSOP, TI 10 ea	0MDR9Q20	Digi Key Corp							77.20								
Printed CKT BRD, p/n +Y Axis_Rev2 5 ea	0MDR9Q21	Advanced CKTS							894.81								
Metric 316 SS Pan head philips screw, M2.5	0MDR9Q2	McMaster Carr							68.79								
K&S Music Wire .015"X36(25), LXWU94 Rround Brass	0MDR9Q23	Tower Hobbies							20.67								
Lab Pro 10 Snap-Apart Kit K910	0MDR9Q25	Bellin Dynamic Sys Inc.							397.50								
Extension MCX to MCX Plug R-Angle 50 Ohm 3 ea	0MDR9Q26	Pasternack							133.15								
Printed CKT BRD, p/n +Y Axis_Rev3	0MDR9Q27	Advanced CKTS							368.23								
Banana Binding Post Conn Yellow Gold, Pomona electric	0MDR9Q28	Mouser Electronics							213.00								
Binding Post Gold Plated Red, Pomona Electronics	0MDR9Q28	Digi Key Corp							419.21								
Printied CKT Board, CSK_TB1 Rev 1	0MDR9Q29	Advanced CKTS							2306.19								
Samtec Elevated Double row Sockets Strip, 0.100"	0MDR9Q31	Samtec							235.02								
Rubber Bumper w/washer 1/2" base, 1/4"H, Metric Pan	0MDR9Q32	McMaster Carr							9.90								
b) E&S greater than $5k			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Contracts / Transfers			0.00	0.00	0.00	0.00	0.00	0.00	300.00	0.00	0.00	0.00	0.00	0.00	0.00	300.00	500.00
Indirect Cost (30.97%)			0.00	0.00	0.00	390.18	473.18	337.20	3295.14	175.82	690.21	286.87	0.00	0.00	0.00	5648.60	16316.00
ISPPI (14.58% = 90% of 16.2%)			0.00	0.00	0.00	56.89	68.99	49.16	480.43	25.64	100.63	41.83	0.00	0.00	0.00	823.57	2378.87
Monthly Expenses / Projected costs			0.00	0.00	0.00	1650.06	2001.06	1425.98	13934.90	743.54	2918.84	1213.16	0.00	0.00	0.00	23887.54	69000.00
Cumulative Expenses			0.00	0.00	0.00	1650.06	3651.12	5077.09	19012.00	19755.54	22674.38	23887.54	23887.54	23887.54			
Uniform Burn rate			0.00	0.00	6900.00	13800.00	20700.00	27600.00	34500.00	41400.00	48300.00	55200.00	62100.00	69000.00			

D. ESTIMATE LABOR COST SPREADSHEET

Labor Cost Estimates

Engineering Labor	Rate(/HR)	Estimated Hr/Wk 2008	Estimated Hr/Wk 2009	Estimated Hr/Wk 2010	Estimated Hr/Wk 2011	Estimated Labor Hours 2008-2011	Estimated Eng Cost
Lab Manager	$50.00	1	2	3	5	543.6	27,180.00
Astro Eng	$65.00	1	2	3	5	543.6	35,334.00
Software Eng	$65.00	1	2	3	5	543.6	35,334.00
Principle Investigator	$80.00	10	5	3	5	791	63,280.00
						Estimated Engineer Labor Cost	161,128.00
						Estimated Engineer Labor Cost	$233,635.60

NOTE: All engineering labor is estimated. The rates were given by the Principle Investigator. Engineers estimated the time they spent each week dedicated to NPS-SCAT specifically. The number of work days was calculated in the years 2008, 2009 and 2010 (Federal Holidays were accounted

Intern Labor		Total Hours Worked	Labor Cost	Total Cost (Includes Acceleration of 10%)
Intern 1	$15.88	458.5	$7,280.98	$8,009.08
Intern 2	$14.14	508.5	$7,190.19	$7,909.21
Intern 3	$14.14	181.5	$2,566.41	$2,823.05
Intern 4	$14.14	163	$2,304.82	$2,535.30
Intern 5	$14.14	83	$1,173.62	$1,290.98
Intern 5 Overtime	$21.21	25	$530.25	$583.28
Intern 6	$14.14	256	$3,619.84	$3,981.82
Intern 7	$15.88	100	$1,588.00	$1,746.80
Totals				$28,879.52
Inter Labor from 2008				$0.00
Intern Labor from 2009				$13,853.33
Estimated 2011 Intern Labor	$14.14	$221.93750000000	$15,690.98	$17,260.08
			Estimated Intern Labor Cost	$59,992.93

NOTE: Inter labor is a direct calculation from the NPS Payroll System. Two account were used to pay intern R789Q and R7815

Military Labor	Estimated Mil Hourly Rate	Estimated Total Military Labor Days	Estimated Total Military Labor Hours	Estimated Mil Labor Cost
O-5 (aviator)	$70.00	49	392	$27,440
O-4 x2	$57.00	49	392	$44,688
O-4 (aviator)	$61.00	49	392	$23,912
O-3 x10	$47.00	49	392	$184,240
			Estimated Total Mil Labor Cost	$280,280
			Estimated Total Labor Cost	$573,908.53

NOTE: The estimated the total hours worked by military students is 4 mounts on average spent on thesis work. Military Pay is based 2009 Pay scales and includes all special pays. Military hourly rate is base on a years salary divided by the average number of work days (3 year average), based on a 8 hour work day.

NOTE: The number of work days consists of a 4 month period in which the military student works on their thesis. Of that time 1 month will be dedicated to training and getting familiar with the project, during this time 50% will be counted toward the project, approximately 10 days. For the next 1.5 months the student will be completely dedicated the project, approximately 31 days. The last 1.5 months will be dedicated to writing their thesis, of that time 20% will for project documentation, approximately 8 days. Work days will be standard 8 hour days.

Calculation of Military Pay	O-5	O-4	O-4 (Aviator)	O-3
Base Pay	$7,287	$6,326	$6,326	$4,949
Housing	$3,150	$2,928	$2,928	$2,658
BAS	$223	$223	$223	$223
Aviation Pay	$840	$0	$650	$0.00
Total Pay (Monthly)	$11,500	$9,477	$10,127	$7,830

E. ESTIMATED CONTRACTED THERMAL VACUUM AND VIBRATION TESTING COST

Value of Vibe Testing	
Hourly Rate	$210.00
Instrumentation Fees	$300.00
Report Fees	$200.00

Estimated Cost to Qualify NPS-SCAT (VIBE)	
Average Number of Hours Rquired	12
Estimated Cost to Qualify NPS-SCAT EDU	$3,020.00
Estimated Cost to Qualify NPS-SCATFlight Unit	$3,020.00
Estimated Total Cost to Qualify NPS-SCAT Vibe	$6,040.00

Thermal Vacumm Testing	
Rate	$128.00
Instumentation Fees	$300.00
Report Fees	$200.00
Engineer Cost (Hourly Rate)	$81.86

Estimated Cost to Qualify NPS-SCAT (T-VAC)		
T-VAC Chamber Rental Fees		$12,288.00
Estimated Labor Cost		$11,132.96
Estimated Fees		$1,000.00
Estimated Total Cost to Qualify NPS-SCAT T-VAC EDU		$24,420.96
Estimated Total Cost to Qualify NPS-SCAT T-VAC Flight Unit		$24,420.96
Estimated Total Cost to Qualify NPS-SCAT T-VAC		$48,841.92
Estimated Total Cost to Qualifity NPS-SCAT		$54,881.92

Note: The number of hours to qualify a 1U Cubesat is estimated to be week of testing for the EDU and the a week for the Flight Unit. Price is what is charged by NASA for using T-VAC facilities. Assume 1 FTE will be on call accumulating 10 hours, and two will conducting the testing. The testing time will be 4 days of 24 hour operations to complete the testing.

F. TVAC AND VIBRATION FACILITIES COST

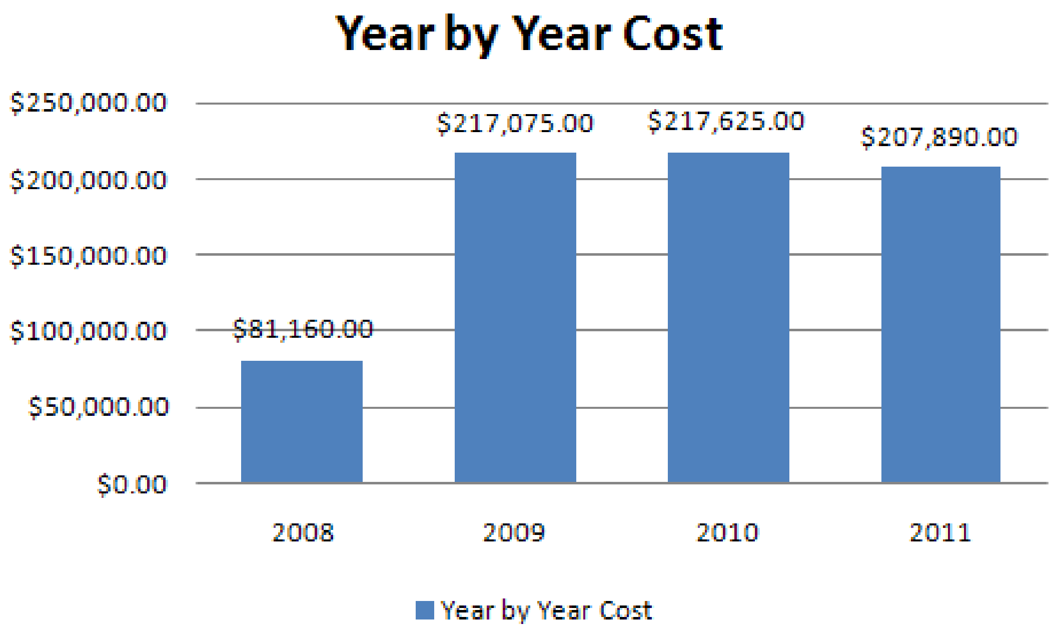
SHAKER FACILITIES COSTS	
Slip Table (FY08):	$15,955.00
6000 lbf Vibration Shaker System (FY07):	$90,620.00
Closed-Loop Vibration Controller (FY06):	$28,125.00
Annual Maintenance on Software (FY10):	$3,774.00
Low-Noise Air Compressor (EST.):	$7,500.00
Triaxial Accelerometers (EST.):	$950.00 Ea.
Uniaxial Accelerometers (EST.):	$213.00 Ea.
Dial Torque Wrench, 3002LDIN (EST.):	$250.00
Dial Torque Wrench, DS1F48CZH (EST.):	$200.00
Miscellaneous Tools (EST.):	$500.00
Consumables (EST.):	$200.00
Total Cost	**$118,799.00**

Tenney Space Jr. Thermal Vacuum Space Simulator Cost	
Chamber	$9,000.00
Estimated Instumentation	$1,000.00
Estimated Support Equipment (Computers)	$2,000.00
Estimated Average Yearly Maintenance (5% of Total V	$600.00
Total Cost	**$12,000.00**

G. ESTIMATED COST OF LAB EQUIPMENT

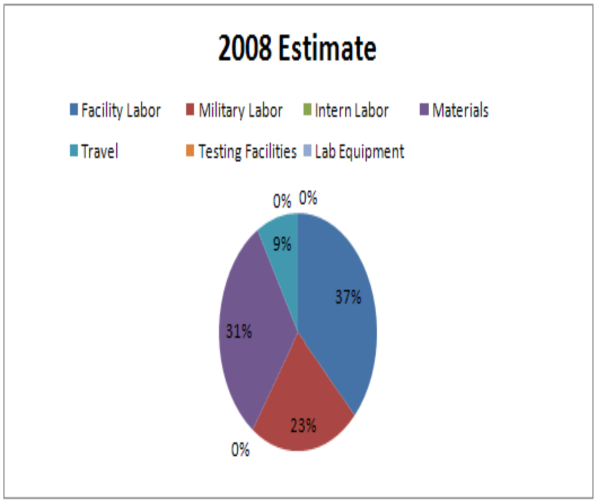
Equipment	Cost/Unit	Number of Units	Total Cost
Aglient 34410A 6 1/2 x5	$1,072.00	5	$5,360.00
Aglient E3631A Power Supply x4	$1,353.00	4	$5,412.00
Aglient3220a Waveform Generator x2	$1,939.00	2	$3,878.00
Tektronic TDS 3034C Digital O-Scope x3	$7,790.00	3	$23,370.00
MasTech MY64 x2	$39.95	2	$79.90
Sony Tecktonix Spectrum Analyzer 3026	$22,500.00	1	$22,500.00
HP Spectrum Analyzer 4396A	$15,995.00	1	$15,995.00
Dell Optiplex 755 W dual Monitors	$800.00	9	$7,200.00
ESD Safe Workbenches x10	$300.00	10	$3,000.00
Total Lab Equipment Cost			**$86,794.90**

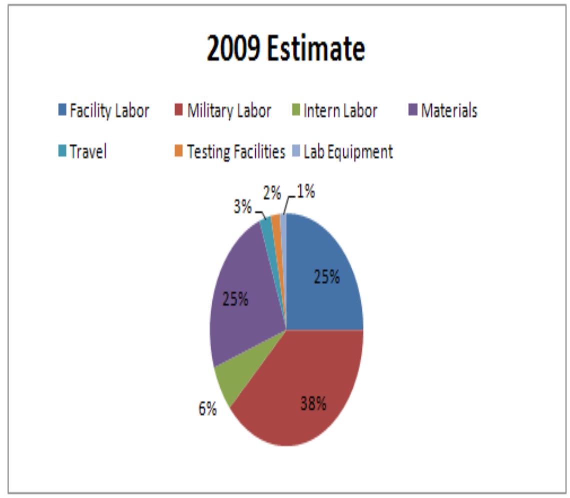
H. ESTIMATED YEAR-BY-YEAR COST

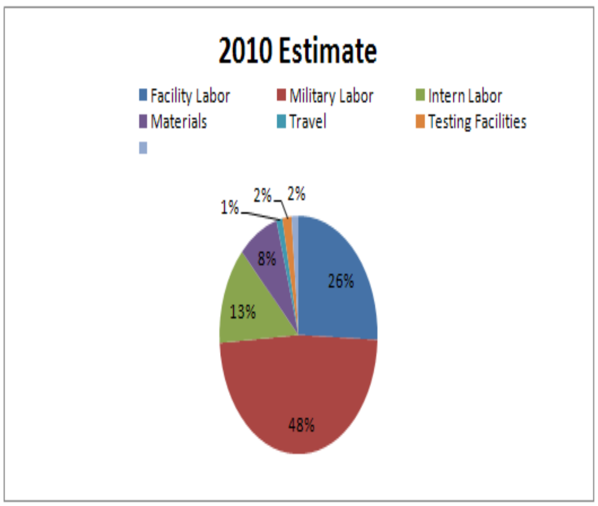


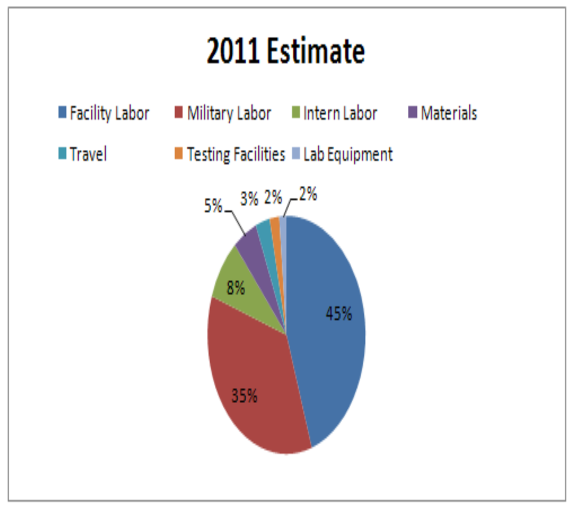
	2008	2009	2010	2011
Facility Labor	$30,160.00	$54,375.00	$55,825.00	$93,090.00
Military Labor	$18,400.00	$83,100.00	$105,100.00	$73,700.00
Intern Labor	$0.00	$13,900.00	$28,900.00	$17,300.00
Materials	$25,600.00	$53,200.00	$17,900.00	$10,500.00
Travel	$7,000.00	$5,300.00	$2,700.00	$6,100.00
Testing Facilities	$0.00	$4,100.00	$4,100.00	$4,100.00
Lab Equipment	$0.00	$3,100.00	$3,100.00	$3,100.00
Totals	$81,160.00	$217,075.00	$217,625.00	$207,890.00

I. YEARLY ESTIMATED COST CHARTS

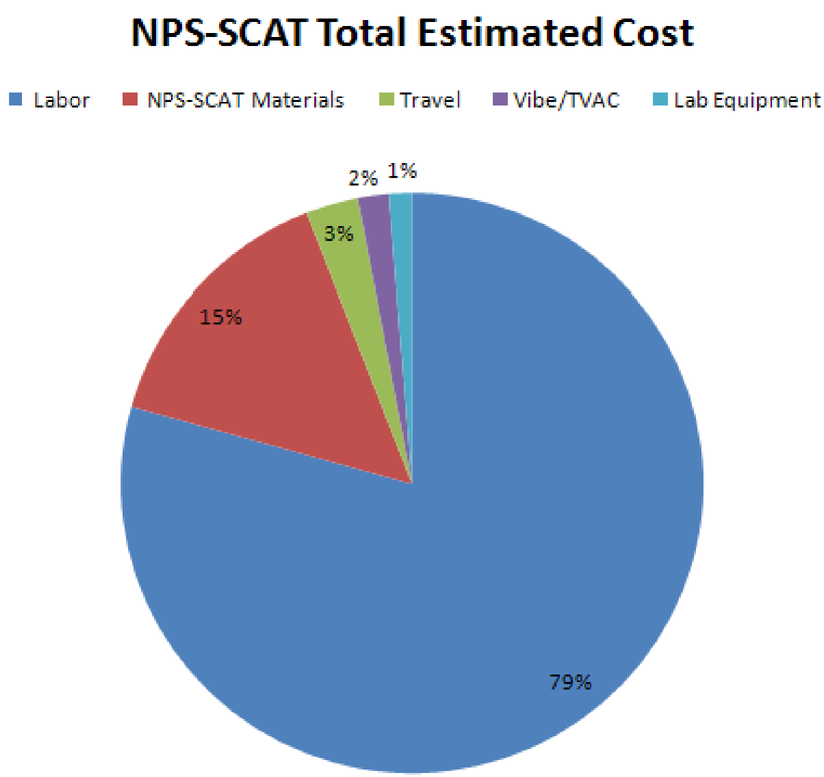






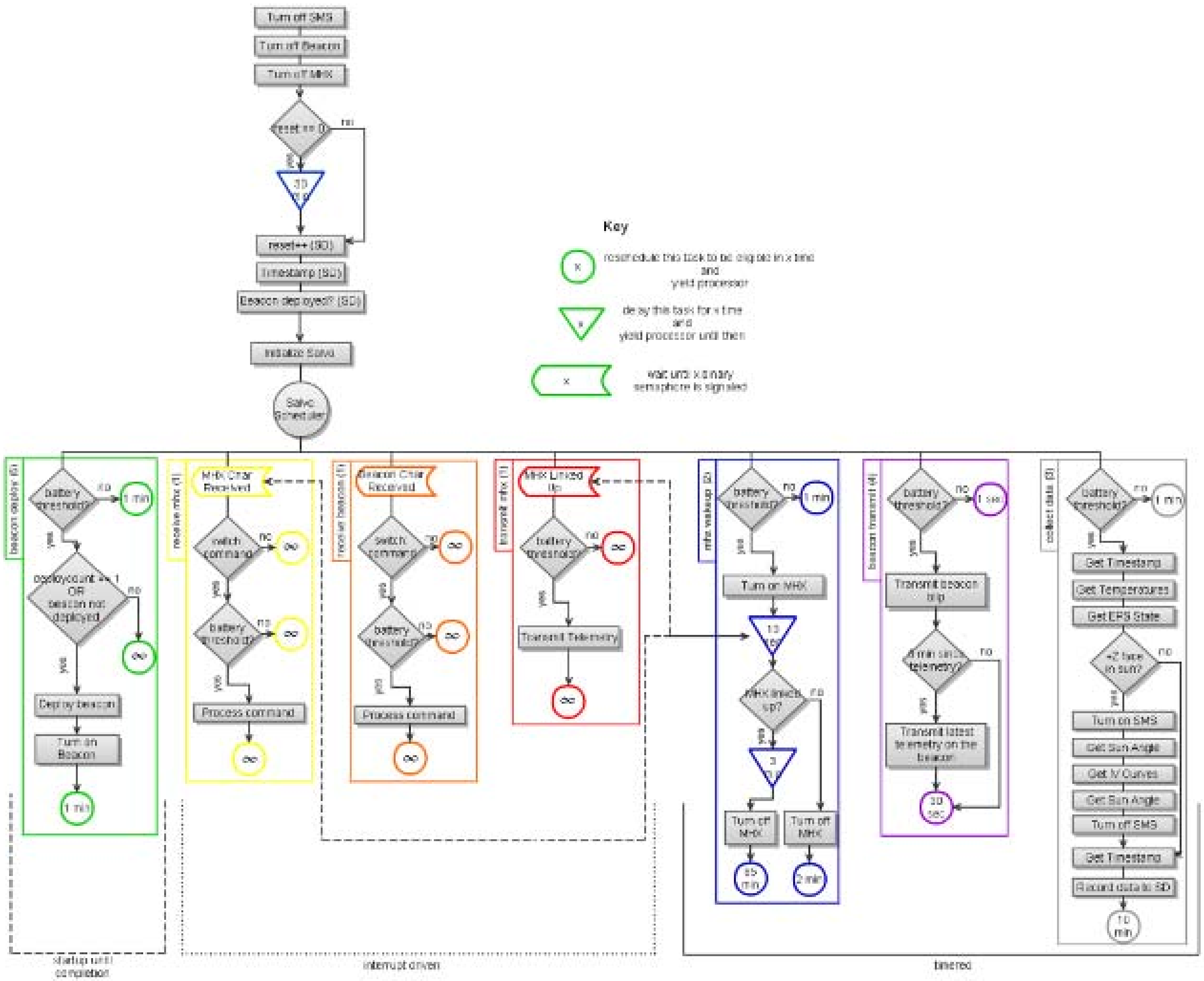


J. ESTIMATED TOTAL COST OF NPS-SCAT BREAKDOWN

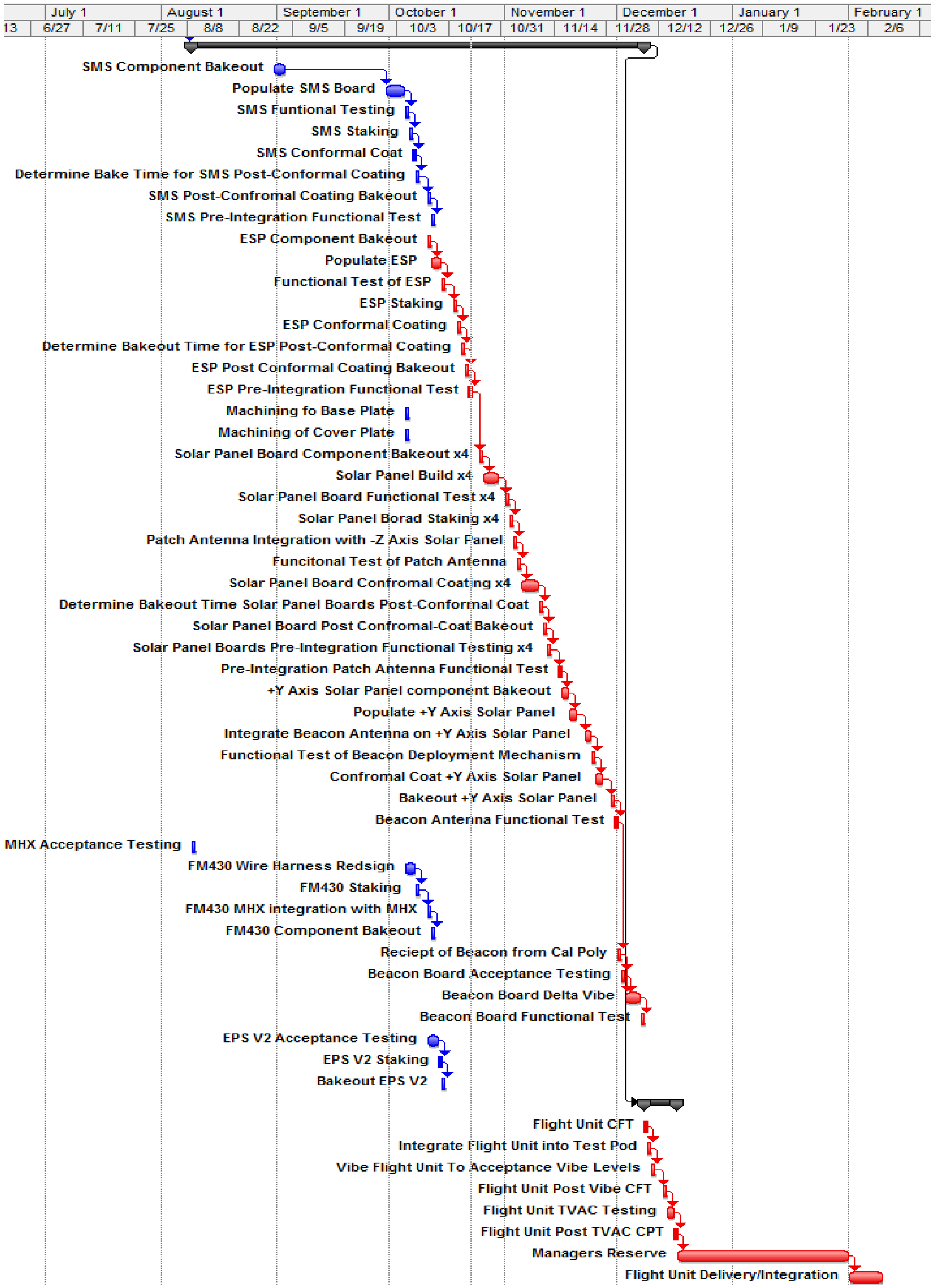


TOTAL NPS-SCAT COST ESTIMATE	
Labor	$573,900.00
NPS-SCAT Materials	$107,200.00
Travel	$21,100.00
Vibe/TVAC	$12,300.00
Lab Equipment	$9,300.00
Total NPS-SCAT Cost Estimated	**$723,800.00**

K. CONOPS DIAGRAM



L. TASK LIST AND GANT CHART



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